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ARMORED MUD BALLS[1]

THEIR ORIGIN, PROPERTIES, AND ROLE IN SEDIMENTATION[2]

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ABSTRACT

A brief summary of the limited literature devoted to mud balls centers around nomenclature, the ideas regarding the origin of mud balls, and the factors limiting their size.

A report is made of a combined field and laboratory study in which an investigation of the size which mud balls may attain leads to conclusions that differ from those in the literature; findings are presented which deal with the relationship between sphericity and the distance mud balls travel, the influence of weight, sphericity, and specific surface upon armor quantity, and the importance of mud balls as a factor in the transportation of debris produced by erosion.

INTRODUCTION

Mud balls, both ancient and modern, are distributed widely throughout the world. For instance, in the United States they are present in the Patuxent formation on the Atlantic seaboard, the Pico formation in California, the glacial drift of the Great Lakes area, and the valley fills of New Mexico, Arizona, and Oklahoma, on

[1] Highly spherical masses of clay studded with pebbles remained unnamed until they were designated "pudding balls" by Cartwright in 1928, apparently because of their superficial resemblance to "pudding stone." Since the pebbles are not commonly distributed throughout the ball, as are plums in a pudding, but are usually restricted to the area at or near the surface where they form a protective coat, the author suggests the term "armored mud balls" as one which is more truly descriptive.

[2] Published with permission of the Soil Conservation Service, U.S. Department of Agriculture.

the shores of lakes with beach cliffs of clay wherever they may be located, and in hundreds of streamways in the southwestern quarter of the nation where the ephemeral nature of the streams makes it particularly easy to find them in large numbers.

Despite their ancient lineage and wide distribution they belong in a geological "no man's land," the category Kindle[3] has suggested for concretions, which they often closely resemble. It is surprising that a search of publications in English discloses only three short papers, all closely related, devoted exclusively to mud balls.[4] Two of these actually are more concerned in showing that some concretions may have originated as mud balls than in imparting information about mud balls as such.

Under various names[5] mud balls have received brief and infrequent mention in the geological literature of the past sixty or seventy years. In 1875 Jones and King[6] wrote of "clay galls" as much as 20 inches in diameter, upon the surfaces of which flint pebbles had become imbedded. During the present century Gardner, Haas, Ellis, Twenhofel, Wentworth, Cartwright, and others have written briefly of similar, though smaller, armored balls.[7] Ellis alone seems to have

[3] E. M. Kindle, "Range and Distribution of Certain Types of Canadian Pleistocene Concretions," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 609.

[4] James H. Gardner, "The Physical Origin of Certain Concretions," *Jour. Geol.*, Vol. XVI (1908), pp. 452–58; Leroy Patton, "In Support of Gardner's Theory of the Origin of Certain Concretions," *Jour. Geol.*, Vol. XXX (1922), pp. 700–701; William H. Haas, "Formation of Clay Balls," *Jour. Geol.*, Vol. XXXV (1927), pp. 150–57.

[5] Balls, galls, pebbles, cobbles, and boulders of clay and mud are commonly mentioned. Balls are highly spherical masses of clay produced in streams or other bodies of water. Galls are clay flakes, such as are commonly seen curling up on sunny floodplains, which have been incorporated in sand deposits, frequently after their shapes have been altered by breaking or rolling. In the nineteenth century even large clay balls were referred to as galls. Pebbles, cobbles, and boulders differ from one another only in size, the limitations being the same as for stones. Frequently they appear to have been shaped by flowing water rather than by being rolled along a smooth bottom, as in the case of balls.

[6] Rupert T. Jones and C. Cooper King, "On Some Newly Discovered Sections of the Woolwich and Reading Beds," *Quart. Jour. Geol. Soc. London*, Vol. XXXI (1875), pp. 451–57.

[7] Gardner, *op. cit.;* Haas, *op. cit.;* A. J. Ellis, a portion of a paper on clay balls recovered from glacial outwash published by Haas (*op. cit.*, pp. 152–53) in 1927; William H. Twenhofel, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins, 1932), p. 694; Chester K. Wentworth, "The Terminology of Coarse Sediments," *Nat. Res.*

made laboratory studies, the results of which were published in part after his death by Haas. The bulk of his work apparently has never been made available.

THE ORIGIN OF MUD BALLS

As to the origin of mud balls Gardner[8] suggested in 1908 that in the "super-saturated" streams of the Southwest a soft nucleus is formed by the cohesion of fine clay particles as they flow along a smooth bottom, in much the same way that butter is formed in a churn. These, he said, grow by the adhesion in concentric layers of clay, sand, pebbles, and other materials until the stream is no longer able to turn over the mass.

Gardner's view of the origin of mud balls differed radically from the one set forth by Jones and King[9] in 1875. The armored balls found upon beaches, they suggested, were formed by waves rolling chunks of clay that had fallen from neighboring cliffs. It is obvious from the text that these gentlemen were expressing an idea already generally accepted.

For nearly twenty years Gardner's hypothesis went unchallenged. Then, in 1927, after field investigations in the Southwest, Haas expressed doubt that large balls could be formed as Gardner suggested and added: "Of the scores which the author has broken apart not a single one showed a concretionary structure."[10] Haas agreed, however, that the size which balls may attain is determined by the ability of the stream to turn over the mass, and added "or by the narrowest part of the channel through which they have come."[11]

Coun. Bull. 98 (1935), p. 241; Lon D. Cartwright, Jr., "Sedimentation of the Pico Formation in the Ventura Quadrangle, California," *Bull. Amer. Assoc. Petr. Geol.*, Vol. XII (1928), p. 254.

[8] *Op. cit.*, pp. 454–55. Charles Terzaghi's studies on clay, first published in English seventeen years after Gardner suggested this hypothesis, show definitely that such a mass could not possibly be formed in the manner suggested. Gardner would have made no such error had Terzaghi's works been available to help him differentiate between the minute electrophysical forces of flocculation and those enormous surface-tension forces which are present when clay is in a plastic, semisolid, or solid state. Terzaghi found pressure intensities approaching 5,000 pounds per square inch in a blue marine clay as it reached its shrinkage limit (*Principles of Soil Mechanics* [McGraw-Hill Publishing Co., 1926], pp. 13 and 27).

[9] *Op. cit.* [10] *Op. cit.*, p. 157. [11] *Ibid.*

FIG. 1.—In Las Posas barranca. The beginning of the "assembly line" in a very productive armored mud ball factory in Ventura County, California.

The "pudding balls" found in the Pico beds of Ventura County, California, by Cartwright were occasionally of a concentric, banded structure as well as studded with pebbles. He suggests that they may have been "formed by accretion around a clay nucleus, such as a flake curling up between dessication [*sic*] cracks, which was caught by the renewed flow of a stream over its muddy bed, or the wash of sea water over a mud flat."[12]

FIG. 2.—Stranded mud balls. In times of flood a stream may produce mud balls in large quantities. The balls above were left stranded ten days before this picture was taken by Dr. N. A. Christensen. Many of the balls studied by the author were recovered from a small area adjoining this at the lower left.

Following the hurricane of mid-September, 1936, Kindle[13] observed clay balls as much as 10 inches in diameter on the beach at Cape May, New Jersey. Apparently these had been eroded recently

[12] *Op. cit.*, p. 254.

[13] "Post Hurricane Sea Shore Observations," *Amer. Midland Naturalist*, Vol. XVIII (1937), pp. 426–34; also Carey Croneis and David M. Grubbs, "Silurian Sea Balls," *Jour. Geol.*, Vol. XLVII (1939), pp. 598–612.

from beneath silty beds near the beach. Richter[14] states that clay balls may be formed beneath the surface of shallow seas by the erosion of older tidal deposits.

Twenhofel[15] also records the existence of concentrically banded balls and concurs with Wentworth[16] in the now generally accepted explanation that most mud balls are molded and abraded from chunks of clay which fall from the banks or are torn from the bottom of a stream or other body of water (Figs. 1 and 2). Both Twenhofel and Wentworth noted armoring and explained this as the accretion of pebbles and other substances to the mud balls through pressure. It thus becomes evident that concentric banding results when circumstances permit the accretion of clay fragments and other materials in alternate layers.

Ellis[17] noted that the pebble-filled exterior of balls could be peeled readily from the clay core and shared with Jones and King the distinction of reporting balls having diameters as great as 20 inches. Those mentioned by the other writers were, almost without exception, not over a foot in diameter and usually much smaller.

OPPORTUNITY FOR STUDY

Thus, briefly, may the literature of mud balls be reviewed. Recognizing the paucity of information available upon this interesting subject, we undertook field and laboratory studies under the most fortunate circumstances during the second half of 1938.

The mud balls themselves were supplied in superabundance by Las Posas barranca between El Rio and Camarillo, California. Literally tens of thousands of excellent specimens had been formed by this stream during a major flood, which inflicted severe damage upon Southern California during the first week of March, 1938.

Fortunately for the investigators, specimens were deposited in large numbers within a few feet of U.S. Highway 101 where, many months after the flood, they could readily be collected (Fig. 2). Those which had been exposed to the air were badly disintegrated

[14] Rudolph Richter, "Die Entstehung von Tongeröllen und Tongallen unter Wasser," *Flachseebeobachtungen zur Pal. u. Geol.*, XVI, *Senckenbergiana*, Band VIII, Heft 5/6 (1926), pp. 305–15.

[15] *Op. cit.*, pp. 693–94. [16] *Op. cit.*, p. 241. [17] *Op. cit.*, pp. 152–53.

and apparently confirmed a statement by Haas that they are never preserved unless completely covered at the time of the wash (flood). More than 200 balls, all freshly excavated, were selected for laboratory analysis, and additional hundreds were examined in the field.

So numerous were the balls that they formed an important part of a fill (Fig. 3) which had virtually obliterated a channel approximately 4 feet deep and 20 feet wide, made useless a triple culvert of con-

FIG. 3.—Cross section of a deposit of armored mud balls, Las Posas barranca, Ventura County, California. Large ball at left is approximately 12 inches in diameter. Knife at center gives scale.

crete, each rectangular section of which was 6 feet square, and had rolled by the thousand onto adjacent acres of farmland.

An investigation of the upstream conditions showed that Las Posas offered unusually favorable opportunities for studying the formation of mud balls. About $3\frac{1}{4}$ miles from Highway 101 the stream drops more than 50 feet through a concrete structure composed of a series of 5 deep, cylindrical, cushion pools.

Mud balls which formed above this structure—and they were plentiful—apparently were annihilated in passing through, since

none was found for about 1,000 feet below it, and in the next 1,500 feet only very irregular clay cobbles and boulders were present. These contrasted strikingly with the highly spherical, heavily armored balls which were present in considerable numbers above the structure.

Half a mile downstream from the cushion pools a landslide involving several acres has been slipping into the barranca for half a century or more, forcing the water against the opposite bank, which is now vertical and fully 50 feet high. Of the 6 clays found in the balls of the deposit at Highway 101 (3 miles farther downstream) the 3 most commonly encountered were available here in enormous quantities (Fig. 4*a* and *b*). Evidently clay blocks which reached the stream, even though they could not be transported, were rounded rapidly by the water which flowed around them (Fig. 4*c*). About 1,000 feet farther downstream irregular clay cobbles and boulders were commonplace, but armored balls were not to be found (Fig. 4*d*).

Half a mile from the landslide nicely rounded clay boulders were abundant both on the surface and as exposed in gravel banks (Fig. 4*e*). Fairly good balls studded lightly with pebbles could be found with little difficulty. After another half-mile the lightly armored balls greatly outnumbered the clay cobbles and boulders. One unusually large specimen with a mean diameter of about 20 inches was found (Fig. 4*f*).

For another mile the streamway continued as a deep barranca, and increasingly spherical balls, into which pebbles were more and more deeply pressed, were to be seen stranded in many places or buried in bars laid down by previous floods. Evidence was everywhere to be had that this stream habitually produces excellent armored balls in time of flood.

A little less than 2 miles from the landslide the stream debouches upon the Plains of Oxnard and $1\frac{1}{4}$ miles farther on reaches Highway 101. The entire lower reach had been aggraded extensively during the March flood and subsequently had been excavated by a power shovel for a distance of nearly a mile. In the sides of this restored channel good specimens of armored balls were seen frequently. The increase in both armor and sphericity was observed readily as one journeyed the $2\frac{3}{4}$ miles from the slide to Highway 101.

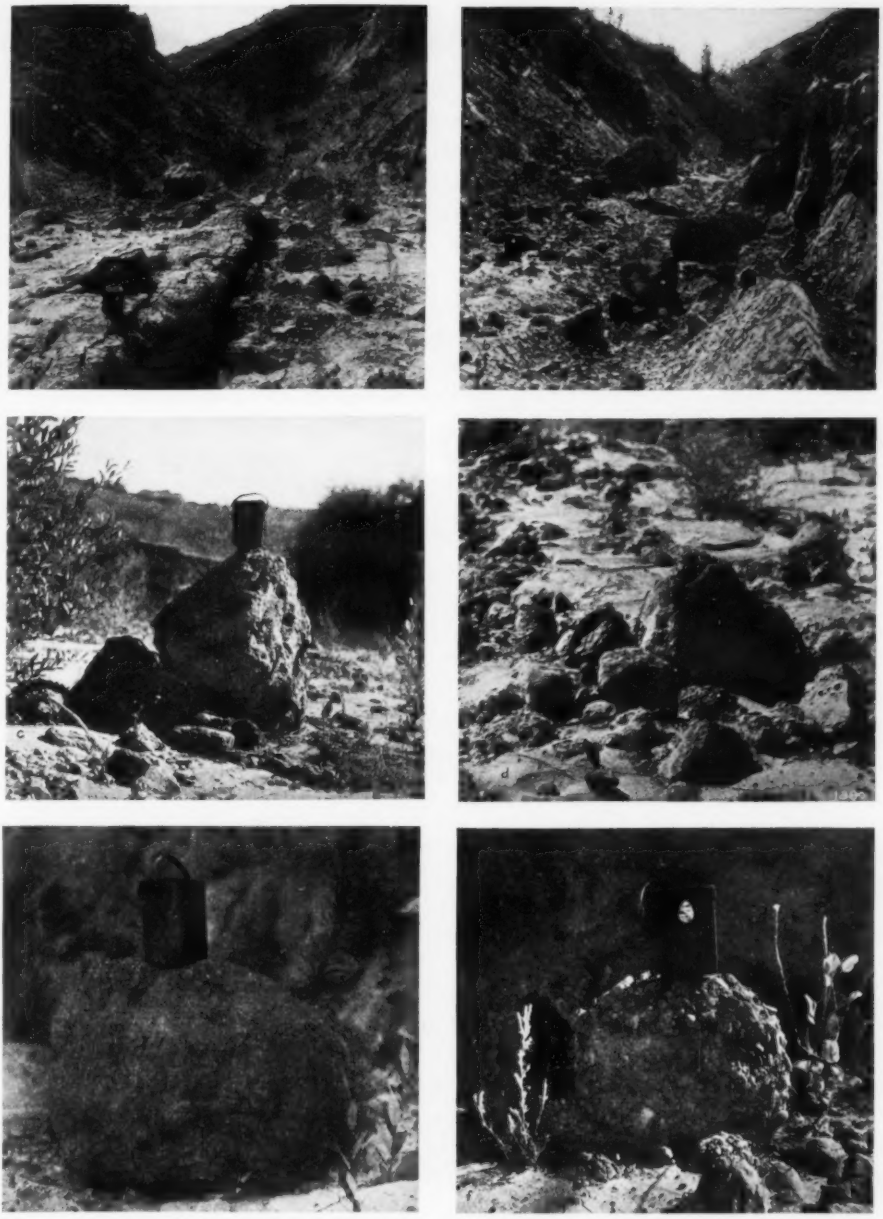


FIG. 4.—The development of armored mud balls. *a*, clayey material available from stream bed; *b*, material available from caving banks; *c*, clayey block rounded by flow of stream; *d*, clay boulder and cobbles after rolling approximately 1,000 feet; *e*, large clay boulder formed by rolling about 2,500 feet; *f*, ball armored after rolling about 1 mile.

Figure 3 shows a vertical section of a portion of the deposit from which the balls for laboratory study were recovered. The 2 balls at the extreme left, being respectively 2 and 12 inches in diameter, show the size range to be quite as great as might be expected in a bed of ordinary pebbles, cobbles, and boulders. A sample of 161 specimens, including those illustrated and others immediately adjacent, had a mean diameter of 2.9 inches and a frequency of occurrence greater than 1,000 per cubic yard. Since the yardage of the new deposits certainly ran into the hundreds and probably into the thousands, it is apparent that the number of balls produced by this stream during the March flood was enormous.

SIZE

Returning to the question of size, it may be well to recall that Gardner and Haas agreed that the size attained depended upon the power of the stream to turn over the mass. If this assumption is valid, is it not strange that, although there was abundant evidence that clay chunks over 30 inches in diameter were moved during the March flood, the largest mud balls commonly found were about 1 foot in diameter, and of the thousands seen not a dozen exceeded 14 inches? Two that had not been transported more than a mile had average diameters of approximately 20 inches.

Field observations indicate that only a fraction of 1 per cent of stream-made mud balls have diameters as great as 1 foot, although much larger masses could be transported easily by many streams in which small balls abound. When one recognizes that some balls grow by accretion while others are reduced in size by corrasion,[18] it becomes evident that the problem is a double one which involves not only the size to which a ball may attain but also the size it may maintain.

An analysis of the problem indicates that it is not one of transportation, as has been assumed, but rather one of structural strength wherein the forces tending to hold a ball together are opposed by those tending to destroy it. Cohesion is called upon to resist the destructive forces of impact, and the power to resist is quite obviously

[18] See Haas, *op. cit.*, p. 153.

proportional to the area under stress. In spheres the cross-sectional area varies directly as the square of the diameter, and it follows that, other factors being constant, a ball having twice the diameter of another offers four times as much resistance to any force which tends to break it in half.

But what of the impact forces to which a ball moving with a given velocity will be subjected upon striking a fixed object? These are obviously just as directly related to the mass of the ball as are the cohesive forces to its cross section. The mass of a ball increases as the cube of its diameter, and therefore the ball with a doubled diameter will be subjected to impact forces not four but eight times their former value. Therefore, it seems reasonable to believe that the size a ball may attain or maintain is determined by the point at which these factors reach a balance. For a ball of a given diameter, moving at a given velocity, the exact location of this point is determined largely by the cohesive strength of the particular clay involved, and with any clay this decreases with increasing wetness.

In an effort to establish the relationship between the forces of cohesion and impact, 40 freshly excavated balls of random sizes were dropped upon a concrete base from certain calculated heights. It was first thus determined that balls approximately 4 inches in diameter would just break when dropped 4 feet. Then it was assumed that a constant might be obtained by multiplying the square of the diameter D^2 of any ball by the height h it must be dropped to break it. When both lengths are measured in inches this constant, as indicated by the 4-inch ball, is $16 \times 48 = 768$.

A 2-inch ball tossed 15 feet into the air cracked so deeply when it struck that it was broken nearly in two ($D^2h = 720$); another, 8.6 inches in diameter, broke cleanly when dropped 10 inches ($D^2h = 740$). A 9.7-inch ball was dropped from a height of 8 inches (753) and broke; and, finally, a 9-inch ball, dropped 8 inches (648), was so deeply cracked that it fell apart when an attempt was made to lift it.

These tests indicated that the assumption was reasonable. Some 35 balls dropped from various heights during further investigations gave rather conclusive proof that if D^2h had a value of 740 or more, a

clean break could be expected. With rare exceptions, if this value was less than 650, the ball was not broken, and in only one case did a ball hold together when this value exceeded 740.

The assumption that D^2h is a constant is apparently justified by these tests, but it should be kept in mind that the suggested numerical value (740) is not universally applicable. Had the balls tested been either wetter or dryer, for instance, a different value would have been obtained.

The determination of an approximate value for this constant makes it possible to calculate that a ball, similar to those used in the experiment, having a diameter of 7.9 inches would break if dropped 1 foot, while a drop of 1 inch would insure the destruction of a ball 27.2 inches through. A determination of the attained velocity shows that the small ball would be traveling 8 feet and the large one only 2.25 feet per second at the instant of impact. This throws much light upon the question of the maximum size a ball may attain or maintain.

Gilbert[19] has made measurements which indicate that the velocity of a bed-load particle once set in motion amounts to about 0.5 0.8 of the mean velocity of the stream, the higher values being valid for larger particles in shallow water—pertinent ones in the case of mud balls.

A ball 27.2 inches in diameter having a density of 1.7 will weigh about 650 pounds. Since ordinarily it must be abraded and molded from an even heavier chunk, let it be supposed that a clay cube of the specified density and with sides equal to the diameter of the ball, fell into a silty stream which had a specific gravity of 1.2. In air the cube would weigh approximately 1,235 pounds, but since it would displace 872 pounds of silty water, its effective weight in the stream would be only 363 pounds. If the stream had a mean velocity of 5 feet per second, the force it could exert upon the mass would be approximately 165 pounds[20]—less than one-half the effective weight of the cube.

[19] G. K. Gilbert, "The Transportation of Debris by Running Water," *U.S. Geol. Surv. Prof. Paper 86* (1914), p. 200.

[20] According to R. R. Daugherty (*Hydraulics* [New York: McGraw-Hill Book Co., 1937], p. 332) this force $= C_f wAv^2/2g$ when C_f = friction drag coefficient; w = specific weight of the fluid in pounds per cubic foot, A = cross-sectional area in square feet, v = velocity of the stream in feet per second, g = acceleration of gravity in feet per second.

Chang[21] states that theoretically a particle's effective weight in water is 40 per cent greater than the force required to move it along the bed. If this relationship holds for particles the size of our hypothetical cube, a velocity of 6.4 feet per second would be required to move it.

Once set in motion a bed-load particle rapidly attains its ultimate velocity, as many bed-load students agree, and our huge clay block would soon be moving at a speed of more than 5 feet per second—over twice the velocity needed to destroy it if it should strike any fixed object squarely. In such a stream, balls with diameters of 8 inches might survive nicely, but all larger ones would be in grave danger of destruction.[22]

Although the variables which affect the formation of clay balls are numerous, the students of sedimentation should be able to gain much qualitative information regarding upstream conditions which existed at the time any group of mud balls was being formed by carefully studying the balls themselves.

Assuming that the balls studied are typical—and there are admittedly insufficient data available to justify such an assumption—if the diameter of the largest ones commonly found in a deposit is approximately 8 inches, the maximum velocity of the stream in which they were formed was probably in the neighborhood of 8 feet per second, since balls of this size may be expected to break up at that speed if they strike any obstruction squarely. In such a stream, according to Gilbert, the maximum speed the bed load could attain would be 6.4 feet, certainly perilously close to the limit an 8-inch ball could endure. Balls a foot in diameter would indicate velocities of not over 5 feet per second, a velocity only slightly greater than is required to move them. Four-inch balls would indicate a stream velocity of 16 feet per second; 2-inch balls a velocity twice as great. One should not lose sight of the fact that small balls might result in streams of low velocity when only small chunks are initially available, as might be true when varved clays are involved.

[21] Y. L. Chang, "Laboratory Investigation of Flume Traction and Transportation," *Proc. Amer. Soc. Mech. Eng.*, Vol. LXIII (1937), pp. 1729 and 1737.

[22] In making these calculations many assumptions have been made, perforce, and values given are to be taken only as rough indications of the order of magnitude of forces and sizes.

The rolling process is essential to the formation of clay balls with high sphericity, and, therefore, unless clay chunks can roll freely, such balls cannot be expected to develop. It is of interest, in this connection, that the mud balls observed in this investigation and during the previous 10 years invariably have been large in comparison with the average size of the particles which formed the bed of the stream that produced them (Fig. 3). It follows that clay "golf balls" will not be produced in a stream the stable bed of which is composed largely of stones the size of grapefruit, oranges, or even golf balls. During periods of low water and moderate velocities the clay fragment would find itself in some snug cranny, and when floods came it would be crushed or smashed to bits by the heavier elements of the bed load. Clearly the size of the particles which form the stream bed tends to limit the minimum size of the balls which may be produced. Like balls of maximum size, then, the smallest balls may record facts about the stream which made them.

Too, the mere presence of clay balls in considerable numbers indicates that the parent stream was cutting laterally and possibly downward at a rapid rate at the time of their formation and that its banks or bed contained large quantities of clay. Conditions that lead to extensive undercutting of banks or to rapid headward erosion are ideal for the production of clay balls.

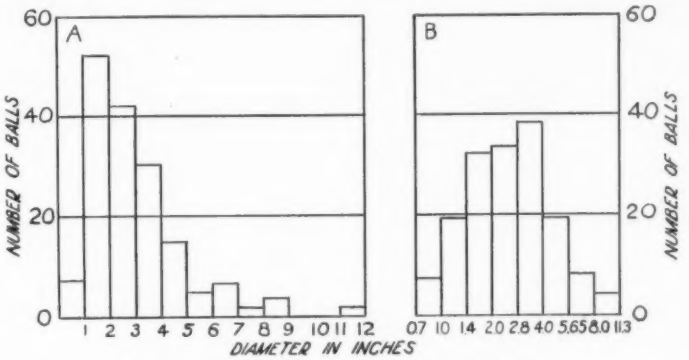
SPHERICITY

The most striking characteristics of the Las Posas balls recovered at the roadside deposit are their high degree of sphericity[23] and uniformly heavy armor of pebbles. In computing the sphericity values, Wadell's[24] method was used. The ratio between the diameter of a sphere having the same volume as the ball and the longest diameter

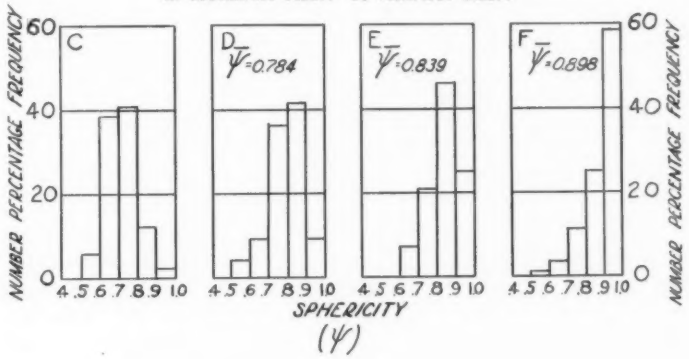
[23] "Wadell appears to be the first to differentiate between *shape* (sphericity) and *roundness* and to show that these are two independent variables. Wadell pointed out that roundness was a matter of the sharpness of the corners and edges of a grain, whereas shape has to do with the form of the grain independently of the sharpness of its edges. . . . Wadell, therefore, used the sphere as a standard of reference and spoke of the 'degree of sphericity' as the measure of the approach of other solids to the sphere in form" (W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography* [New York: D. Appleton–Century Co., 1938], p. 283).

[24] Hakon Wadell, "Shape Determination of Large Sedimental Rock Fragments," *Pan. Amer. Geol.*, Vol. LXI (1935), pp. 187–220.

of the ball was obtained. The volume was computed using the three diameters and the equation for the volume of a triaxial ellipsoid.



SIZE-FREQUENCY DISTRIBUTION OF 161 MUD BALLS FROM LAS POSAS BARRANCA, VENTURA COUNTY, CALIFORNIA.
A. Arithmetic scale. B. Geometric scale.



SPHERICITY DISTRIBUTIONS COMPARED.

C. Beach pebbles from Little Sister Bay, Wisconsin. (After Krumbein and Griffith) D. Clay pebbles, cobbles and boulders after rolling about a quarter of a mile in Las Posas Barranca. (55 specimens) E. Clay pebbles, cobbles, boulders and balls after rolling about one mile in Las Posas Barranca. (76 specimens) F. Clay balls from Las Posas Barranca after rolling about 2 3/4 miles. (161 specimens)

FIG. 5

The results of these calculations are shown graphically and compared with a sample of beach pebbles as presented by Krumbein and

Griffith[25] (Fig. 5, *C* and *F*). Notice that nearly 60 per cent of the balls have sphericities which exceed 0.9. What cannot be learned from the histogram is that 32 per cent had sphericities above 0.95, 12 per cent above 0.99, and nearly 7 per cent had a sphericity of 1.00. Measurements were made only to the nearest tenth of an inch; even so, it is noteworthy that one ball in each 14.6 qualified as a sphere.

The high average sphericity of mud balls is not without importance. Gilbert[26] has pointed out that a particle may be transported in four ways, depending upon its shape, size, and density. It may slide along the bottom, it may leap, it may roll, or it may be carried in complete suspension. Suspended particles move most swiftly, but the rolling ones outstrip those which leap or slide. Clay chunks, by becoming round enough to roll, actually speed up their transportation. Not infrequently such balls have dry interiors while they are in transit, which indicates that much of their initial buoyancy is retained. Both their attained sphericity and their conserved buoyancy tend to increase the efficiency of the destructive forces of erosion by easing the stream's transportation burden.

So rapid is the development of clay balls (Fig. 4) that it seems entirely within the realm of possibility that their attained sphericity might be used with a fair degree of accuracy for estimating the distance to source material. A determination of percentage by weight of armor should increase the dependability of such estimates. Although reasonable accuracy might demand such an elaborate study of the character of the clay involved that it would make the method entirely impractical, data are insufficient at present for conclusions to be drawn.

The idea of using roundness measurements for this purpose has been suggested by Wentworth,[27] who measured river pebbles that had traveled known distances and then constructed a "roundness-distance curve." "One of the most valuable applications of the

[25] W. C. Krumbein and J. Scott Griffith, "Beach Environment in Little Sister Bay, Wisconsin," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 629–52.

[26] *Op. cit.*, p. 200.

[27] "A Field Study of the Shapes of River Pebbles," *U.S. Geol. Surv. Bull. 730 C* (1922), pp. 103–14.

roundness-distance curve," he wrote, "is in determining the distance certain pebbles have traveled by a measurement of their roundness." Not only is the sphericity of mud balls much more readily deter-

FIG. 6*a*.—Group of clay boulders, cobbles, pebbles and balls dug from a gravel bar about $\frac{1}{4}$ mile below their point of origin.

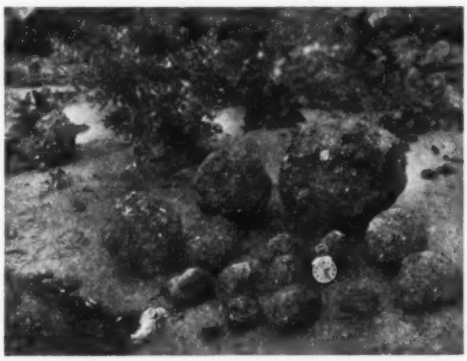


FIG. 6*b*.—Group of lightly armored clay pebbles, cobbles, and balls about 1 mile below their point of origin. Like those in Fig. 6*a*, these were found in a gravel bar. Notice the great increase in sphericity.

mined than is the roundness of pebbles, but also the range of physical conditions under which mud balls are formed is so greatly restricted that their use in estimating distances traveled should be comparatively simple.

With this in mind, three stations were selected at which the specimens measured were known to have traveled approximate distances of $\frac{1}{4}$ mile, 1 mile, and $2\frac{3}{4}$ miles, respectively (Fig. 6*a*, *b*, *c*). Mean sphericities were found to be 0.784, 0.839, and 0.898 at these points (Fig. 5, *D*, *E*, and *F*). These data indicate that in this particular instance the sphericity varies as the cube root of the distance traveled. It must not be forgotten that three points are insufficient to determine the type of a curve accurately and that at zero distance

FIG. 6*c*.—Finished products such as these result when crude clay blocks have rolled approximately 3 miles in Las Posas barranca. Note the remarkably heavy pebble armor and the high degree of sphericity.

the sphericity is not zero but a finite value. For instance, a cube and a block 1 × 1 × 2 have sphericities of 0.716 and 0.637, respectively.

ARMOR

Investigation of the armor held much of interest. Rather convincing proof of the geological period to which the balls belong was supplied by an armor pebble which proved to be a bottle cap. In another case a small finishing nail was incorporated in the armor. Frail gastropod shells were occasionally as perfectly preserved as if they had been packed in cotton. Selenite crystals were sometimes present and scarcely scratched.

Having observed that there was an apparent geometric similarity in the size distribution of the armor particles on balls of various

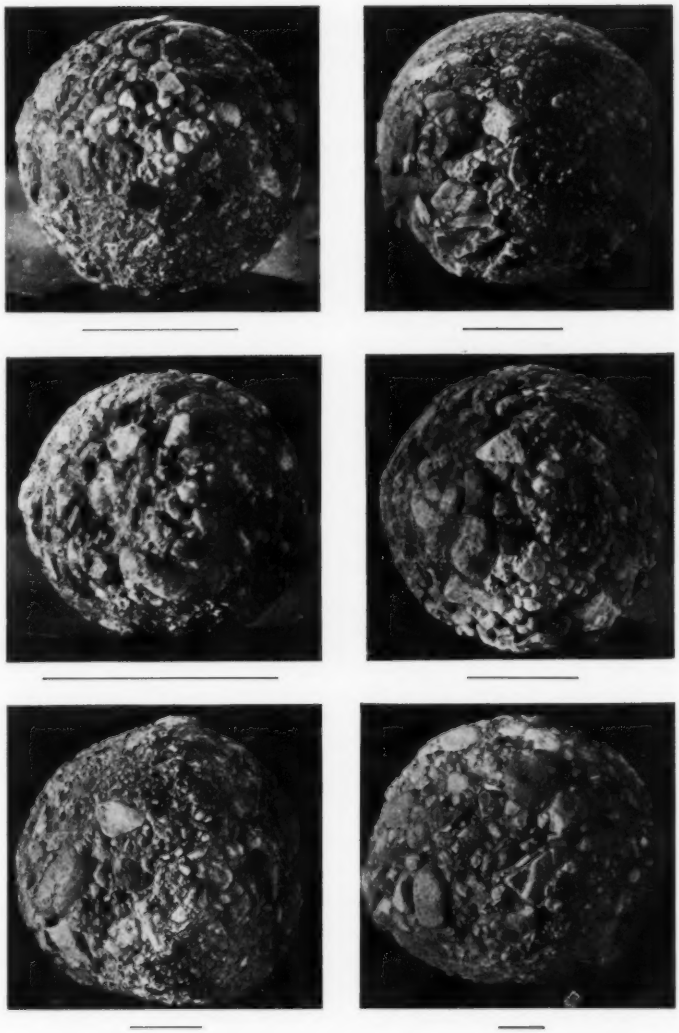


FIG. 7.—Las Posas mud balls. These six balls illustrate the geometric similarity in the size distribution of the armoring particles on balls of widely differing diameters. The line beneath each represents 1 inch.

diameters, we made a series of six photographs in such a way that the photographic image had approximately the same diameter in each case. The resulting pictures are shown in Figure 7 with a line drawn beneath each to represent 1 inch. So convincing was this approach that mechanical analyses were made of the armor of a series of balls. Computations made from these analyses confirmed the photographic evidence of armor similarity. Figure 8 shows the core of a

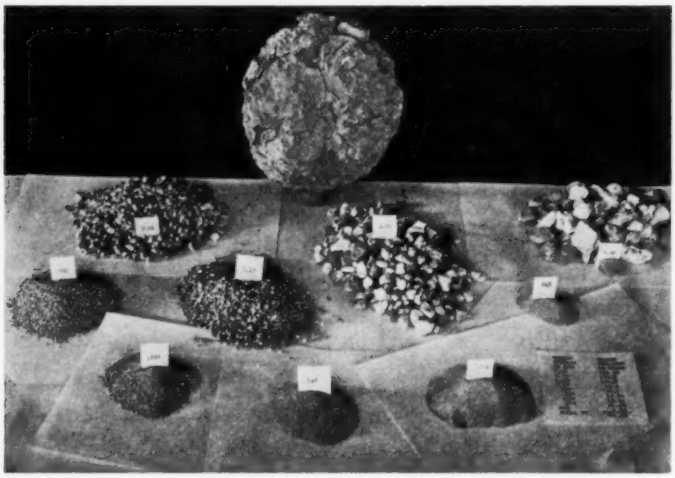


FIG. 8.—A mud ball and its armor. The quantity of armor a single ball may acquire is often astonishing. The armor shown above has been separated into nine grades by sieving. The original ball was just an average one from Las Posas barranca.

large ball surrounded by its armor which has been separated by sieving into nine grades.

In another investigation 47 balls were picked at random, weighed, and stripped of their outer shells which consisted of sand and pebbles held together by a clayey matrix contributed almost entirely by the original core of the ball. All fines were removed by washing, and the remaining coarse material was oven dried and again weighed. This residue was considered to be the armor of the ball, although it was recognized that it contained sand and, in some instances, small con-

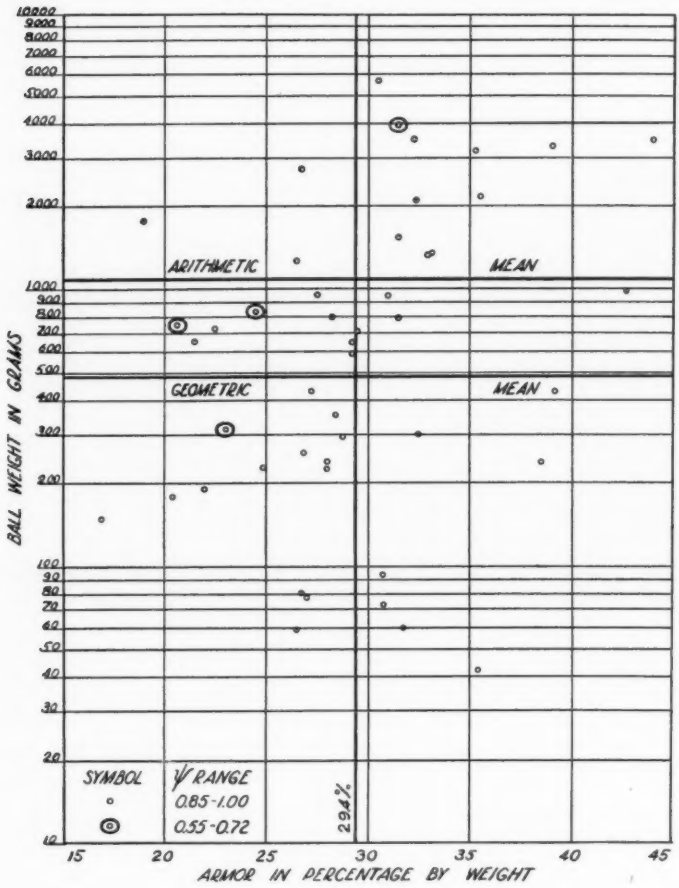
cretions and shell fragments derived from the block from which the ball had developed. In extreme cases as much as 7 per cent of this so-called armor was supplied by the matrix, but the average probably was less than 3 per cent.

The portion of the total weight of a ball that could be attributed to armor varied from 17.1 per cent to 44.0 per cent, the mean value for the 47 balls being 29.4 per cent. The data obtained are shown in a scatter diagram (Fig. 9), which indicates that the general tendency is for the heavier balls to have a higher percentage of armor than the lighter ones.[28] Of the 14 balls with weights greater than the arithmetic mean (1,086 gm.) only 3 had less than average armor. The average for the group was 32.1 per cent. The 26 balls with greater than geometric mean weight (486 gm.) had a group average of 30.3 per cent, and 15 had heavier-than-average armor. There were 21 balls below the geometric mean weight having an average armor weight of 27.5 per cent.

Balls weighing less than 100 gm. appear to constitute a nonconformist group, but the specimens are too few to allow conclusions to be drawn safely. If, however, their remarkably heavy armor is not purely accidental, several reasonable explanations may be advanced: (1) that they are remolded fragments of larger armored balls, (2) that their total weight is so small that the percentage of armor would be influenced greatly by the adherence of a very few large pebbles, and (3) that, since armoring is a surface phenomenon, the influence of a very high surface area per unit of volume is coming into play. A sphere with a diameter equal to unity will have 6 units of surface for each unit of volume, but if the diameter is increased to 4, it will have only 1.5 surface units for each 1 of volume. The effect of this rapidly decreasing ratio apparently is more than offset in all but the smallest balls by the increasing weight which tends to imbed pebbles more deeply. Yet the depth to which a pebble may penetrate is limited also by the thickness of the plastic layer that surrounds a more or less

[28] If the percentage of armor by weight for this same group of balls is plotted against the mean ball diameter, the larger balls and the very smallest balls again show this tendency to armor more heavily than those of intermediate size.

dry center and, consequently, it would not be surprising to find that the armor ratio falls appreciably on balls larger than those already



PERCENTAGE OF ARMOR IN RELATION TO TOTAL WEIGHT FOR 47 MUD BALLS FROM LAS POSAS BARRANCA, VENTURA COUNTY, CALIFORNIA. 1938.

FIG. 9

investigated. The heaviest ball shown in Figure 9 may indicate such a trend. It seems entirely possible, too, that stickiness, rather than

weight, plays the leading role in armoring balls such as the smallest represented in the diagram.

Three of the 10 balls having armor ratios below 25 per cent resembled footballs more closely than spheres (Fig. 10). The same shape characterized the ball with the lowest percentage of armor in the group of 5 weighing between 3,000 and 4,000 gm. (Fig. 9), but the analyses made were insufficient in number to justify the conclu-

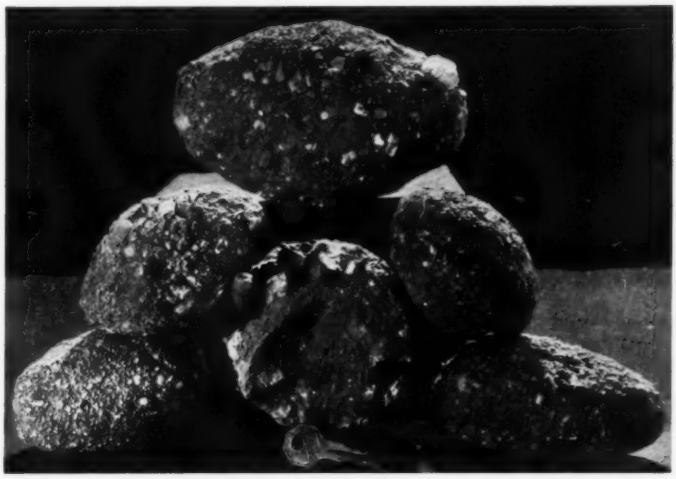


FIG. 10.—Mud "footballs" and "potatoes." Balls of this type were frequently found in the Las Posas deposit. That they tend to become most heavily armored in the region of their minor axis is shown conspicuously by the specimen in the center at the left. It seems probable that the cores originally were elongate blocks.

sion that low sphericity is regularly accompanied by lighter armor. Such a possibility is indicated, however, and examination in the field apparently confirms this view. Furthermore, a ball of the football type tends to revolve exclusively about its major axis and, as a consequence, can become armored heavily only upon its minor circumference.

The rolling process is obviously essential to high sphericity and therefore the farther a clay block rolls—assuming a favorable stream bed—the better are its chances of becoming a sphere (Fig. 5, *D*, *E*, and *F*), the softer its exterior becomes, and the greater is the number

of pebbles with which it comes in contact. Since this increased softness makes it possible for the pebbles encountered to be pressed in more readily and more deeply and since high sphericity allows a ball to rotate on various axes, it is only reasonable to expect heavier armor.

In the balls examined pebbles frequently penetrated for a distance equal to one-fourth the radius of the ball, and sometimes even twice

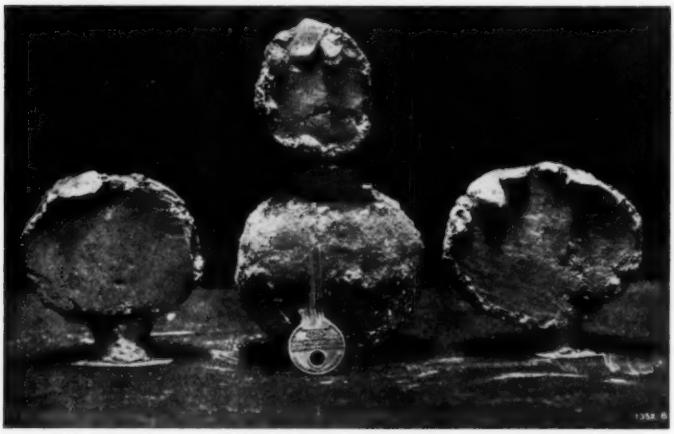
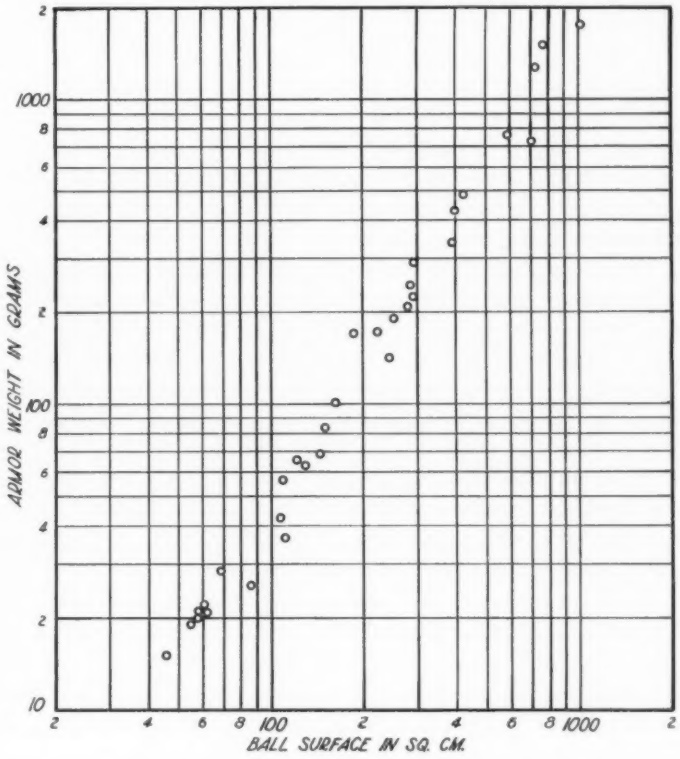


FIG. 11.—Lopsided armoring. Balls such as these may be re-rounded fragments of larger balls which had become armored before breaking to pieces. The small ball in the center is an extreme case.

as deeply, but as a general rule the armoring shell was not very thick. Usually when pebbles penetrated to great depths, they did so on one side only and were of sizes which appeared large for the specimen upon which they were found (Fig. 11). There is good reason for believing that such balls are fragments broken from larger ones which had become armored. It is also probable that the unusually high percentage of armor shown by certain small balls, such as the group of three shown in Figure 9 with weights between 200 and 500 gm., may be explained in the same way.

Obviously, then, the quantity of armor on any ball has been influenced by a host of variables, a list of which would almost certainly

include the permeability, specific gravity, volume, and stickiness of the clay nucleus, the distance it has come and the rate of travel



THE RELATIONSHIP BETWEEN ARMOR WEIGHT AND SURFACE AREA

Thirty-two armored balls from Las Posas Barranca, all with sphericities greater than 0.9, are represented.

FIG. 12

(variables which may greatly influence both size and sphericity), the velocity and specific gravity of the stream, and the availability and density of suitable armoring material. In the wake of this incom-

plete though imposing list, it is clear that conclusions drawn from Figure 9 must be recognized as tentative ones.

Since armoring is essentially a surface phenomenon, it was thought that a method of plotting which emphasized area rather than weight would be more consistent. With this in view 32 balls, all with sphericities greater than 0.9, were selected and their armor weights plotted against their surface areas. Figure 12 resulted and presents a much more convincing picture than Figure 9, even permitting the conclusion that the total quantity of armor is a power function of the surface area and can be expressed, in this case at least, with reasonable accuracy as $W \propto A^{1.54}$.

Thus it becomes evident that the larger balls may be expected to be more heavily armored than the smaller ones, a conclusion that confirms the one previously drawn from Figure 9, namely, that the heavier balls tend to have a higher percentage of armor than the lighter ones. Since the balls varied in specific weight from slightly less than 1.5 to slightly more than 2.0, it can readily be seen that balls of equal size might vary considerably in weight.[29]

The proportionality just expressed indicates that the weight of armor per unit area is approximately a linear function of the ball diameter. This relationship may be stated more generally by introducing the effective specific weight of the ball: thus $W / D^2 = C(\nu_b - \nu_w)D$, where W is the total armor weight, D the diameter of the ball, C the constant of proportionality, ν_b the specific weight of the ball, and ν_w the specific weight of the fluid in which the ball is produced.

SHELLS

In describing the armored balls he recovered from glacial tills, Ellis stated: "The shell was not so firmly fixed to the nucleus it could not be readily peeled off."[30] This characteristic of armored clay chunks probably is almost entirely responsible for the belief that both clay and pebbles commonly are added to the exterior of the

[29] Although all the balls represented in Fig. 12 were formed by one stream during a single flood, they contained clayey cores of at least 6 kinds and varied in weight from 42 to nearly 5,800 gm., and so covered the entire range upon which the laboratory investigations were made.

[30] Quoted by Haas, *op. cit.*, p. 153.

rolling masses and that there is practically no limit to the size which they may reach if only the stream can continue to roll them.

Although occasional balls do show clearly that both clay fragments and rock pebbles have been added to form the armoring coat, the percentage of such balls apparently is small. Ordinarily it is obvious that the pebbles have been forced into the soft outer layer of the clay chunk, and, since the matrix for the armor must be supplied from within, an average ball cannot be expected to increase its size greatly by accretion of pebbles. As soon as it becomes well covered, it has almost sealed itself against any further intrusions. Pebbles which penetrate beyond their own diameters must be driven in by impact against other external hard substances. Just how far they may intrude will depend largely on the depth to which the ball has become wet and to a lesser degree upon the weight of the ball and the velocity of the stream.

A large number, perhaps the majority, of clay balls, whether armored or not, have dry interiors at the time they are deposited. This statement may be questioned by many readers, but recent field studies have shown that the time required to convert an angular clay block into a highly spherical ball with a fair coat of pebbles is frequently less than 15 minutes, while a well-rounded pebble or boulder of clay may be produced in a very few minutes. When this speed of formation is coupled with the rapid decrease in the rate of absorption which accompanies the wetting of dried clay and with a further decrease caused by the acquisition of a coat of armor, it is easily seen that the interior of a ball is very effectively sealed against any rapid penetration of moisture. Such considerations justify Haas's statement that "if they are broken apart shortly after they come to rest, the major part of the interior of the larger ones may be perfectly dry with a moisture penetration of less than an inch."[31]

Because of the way in which balls become armored, it may seem strange that the outer shell peels so readily. If balls were so deposited that only their exteriors ever became wet, the shell probably would not peel. By the very nature of things this is rarely the case, for, although a ball may be quite dry inside when deposited, it is ordinarily gradually wet through after it comes to rest. Taken from

[31] *Op. cit.*, p. 157.

the earth in this condition, the shell clings tightly, but if the ball is exposed to the air for a few hours, or for a few days in the case of large ones, the shell often becomes loose, frequently so loose that it falls off.

The core of a ball usually is composed of relatively pure clay and silt with high shrinkage factors, while the shell contains only from 20 per cent to 50 per cent of such material, the remainder consisting

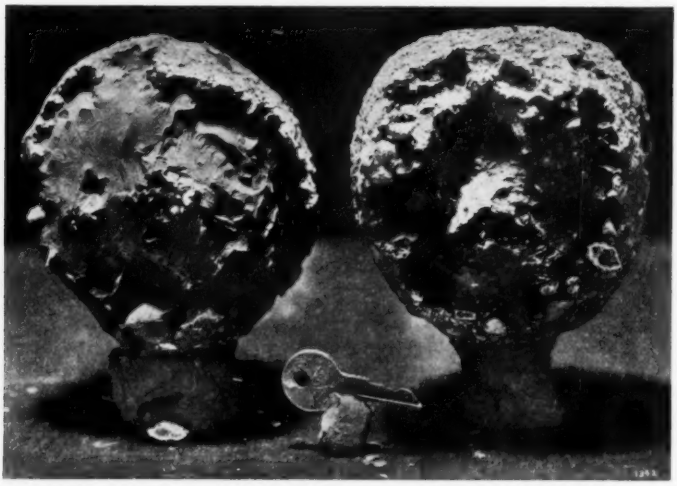


FIG. 13.—Mud balls after drying. Armor has spalled from the ball on the left, leaving the core of fine-grained blue clay intact. The one on the right, composed of coarse-grained, brown, gypsiferous clay, has been deeply penetrated by drying cracks.

of sand, pebbles, and similar substances, most of which have a shrinkage factor of zero.[32] Consequently, when drying takes place after deep wetting, the core actually shrinks away from the shell, which may then be readily removed (Fig. 13).

THE ROLE OF MUD BALLS IN EROSION AND SEDIMENTATION

It may be well at this point to review certain facts which have been previously set forth: (1) blocks of clay rapidly attain high

[32] Thirty-seven shells averaged 30.7 per cent fines and water-soluble material by weight, the extremes being 21.0 per cent and 44.6 per cent.

sphericity while being transported by a stream, (2) bed-load particles that roll travel more swiftly than those that leap or slide, (3) clay balls, by conserving their dry interiors during transportation, frequently retain a portion of their original buoyancy, and (4) approximately 30 per cent of the total weight of the balls examined was supplied by sand, gravel, and other substances picked up in transit by the rolling clay masses.

High sphericity, conserved buoyancy, and the ability to acquire armor combine to make mud balls powerful and efficient vehicles for the transportation of erosional debris as bed load. Therefore, by converting irregular clay chunks into self-armoring balls, a stream may so increase the efficiency of its transportation methods that it may readily roll away enormous quantities of material which it otherwise would be forced to abandon.

Certainly this method of moving debris speeds up appreciably the cutting of gullies in regions where clayey soils predominate. Rough estimates, which are thought to be conservative, indicate that nearly 500 tons of clay and 200 tons of gravel were removed as armored mud balls from $1\frac{1}{2}$ miles of Las Posas barranca during the single flood of March, 1938.

Mud balls make it possible not only to move larger loads but also to move them farther. Ordinarily in debouching upon a fan or into a flood plain, a stream soon abandons the larger units of its bed load and deposits much of its suspended load as well. Alluvial fans themselves are proof enough of this fact. If the stream bed be firm and smooth, mud balls may continue far out into the distributaries, even when the depth of the stream has become less than the diameter of the transported ball.

Since mud balls are large in comparison with the particles which form the stable bed of the streams in which they are produced, it is not strange that they are usually deposited in locations where ordinary cobbles are rare and boulders quite unknown. In such a place in their final role they play the part of the missing stones, and this they do remarkably well (Fig. 3).

CONCLUSIONS

In conclusion, it may be well to summarize and restate the facts which these studies of clay balls seem to show:

1. Almost all mud balls are formed from blocks of clayey material which have caved from the banks or have been torn from the bottom of a stream or other body of water and then have been abraded or molded into highly spherical forms. Terzaghi's studies on the properties of clay make it clear that such balls cannot be formed from soft nuclei in the manner Gardner suggested.

2. Contrary to the belief of Gardner and Haas, the maximum size of balls is not "limited only by the power of the stream to turn over the mass," but by a balance between forces of impact and forces of cohesion. Experiments indicate that the velocity with which a ball may move with safety in a stream is inversely proportional to its diameter. Although armored balls as large as 20 inches in diameter are usually found only in lakes and seas, they occasionally occur in streams at no great distance from the source of their core material.

3. The minimum size of balls appears to vary with the average size of the particles that compose the stable bed.

4. Armored clay balls studied (all from one locality) approach geometrical similarity both in the appearance and in the actual size distribution of their armor particles.

5. A ball armors itself by pressing pebbles into its softened exterior, and, although it may thereby increase in size, a heavy coat of gravel virtually eliminates further growth.

6. High sphericity and complete armoring are the results of rolling upon a relatively smooth stream bed. Other factors being constant, the quantity of armor attained is a power function of the surface area of the ball.

7. The armor coat peels or spalls from a ball because of the relatively high shrinkage of the clay core and the low shrinkage of its pebble-filled "shell."

8. The effectiveness of a stream in removing erosional debris from an area in which clayey materials predominate may be greatly increased by the tendency of clay blocks to attain spherical shape rapidly and to armor themselves readily with gravel.

9. Further careful study of balls formed from a considerable num-

ber of clays under various conditions may furnish geologists with a means of estimating maximum velocities of ancient streams, the nature of their bed material, approximate distances to source material, and the kind of water body which formed them.

ACKNOWLEDGMENTS.—The author gratefully acknowledges his indebtedness to Dr. N. A. Christensen for calling the Las Posas mud-ball deposit to his attention; to Drs. Parry Reiche and Ian Campbell for kindly and constructive criticism; to members of the laboratory staff for willing co-operation, helpful assistance, and generous criticism, and to the Works Progress Administration for the financial aid that made so detailed a study possible. Particular recognition is due Frank F. Batsch, George Osborne, James D. Savage, and Mrs. Muriel Hyde Duer upon whom much of the work has fallen.

A LATE PLEISTOCENE FAUNA FROM HERCULANEUM, MISSOURI

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ABSTRACT

A fauna of mammals and reptiles from a fissure in the Plattin limestone near Herculaneum, Missouri, is described in detail. Most of the genera and species still exist in the vicinity; and on the basis of these the fauna is considered to be late Pleistocene in age, although it contains certain extinct forms, including *Tapirella*, *Megalonyx*, *Tanupolama*, and *Canis dirus*. The assemblage, which includes both forest- and plains-living types, appears to be the result of the activities of the wood rat.

INTRODUCTION

In the spring of 1939 Mr. Clarence Jenni, of Festus, Missouri, called the writer's attention to a fissure in the Plattin limestone from which he had obtained a few mammalian teeth. Subsequently the writer, accompanied by Mr. William Read, of the University of Chicago, excavated the fissure and obtained a small but diversified collection of mammalian and reptilian remains. Sixteen genera of mammals and at least four genera of reptiles were recovered. The fauna is of considerable interest, coming from an area in which little Pleistocene material has been found. This paper deals with the nature of the occurrence and the composition and implications of the fauna.

GEOLOGY

The fissure from which the fauna was obtained was exposed by quarrying operations in the Plattin (Ordovician) limestone. The quarry is located about a mile west of Herculaneum on the north side of Joachim Creek just west of National Highway 61. In this particular area the Plattin is covered only by a thin layer of soil. In places, however, residual cherts, probably mostly Mississippian in age, occur on the slopes of the hills and in the streams. The area, which is one of moderate relief, is drained by Joachim Creek, which flows north and east into the Mississippi River. Forests and grasslands at present support a large vertebrate fauna of mammals, reptiles, birds, and amphibians.

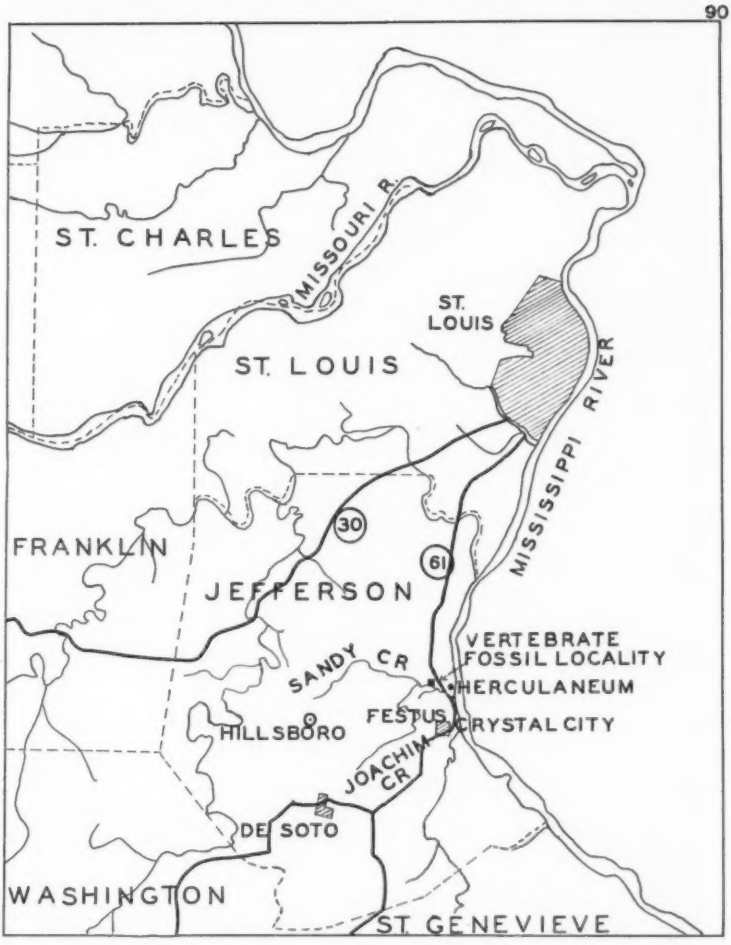


FIG. 1.—Map of area in vicinity of Herculaneum, Missouri, showing location of Herculaneum fissure. Scale: 1 in. = 5 miles (approx.).

FIG. 2.—Photograph of Herculaneum fissure

The fissure is located near the intersection of two joints in the Plattin limestone. One of these joints extends from the surface of the limestone into the rock forming the floor of the quarry and may be traced from one side to the other. The other does not appear in the floor but stops at a level of marked change in lithology of the limestone about 5 feet above the floor. The place of intersection of the two joints has been removed by quarrying. Solution has removed some of the limestone near the junction of the two joints, and the openings have been partially filled by clay and gravel. Coating the limestone in the upper part of the cavity and sealing the fissure above in areas open to observation are thick layers of travertine.

Where excavation of the clay and gravel started, the fissure was about 5 feet wide; but a few feet inward the opening diminished rapidly until, at the point where excavation was stopped, it was less than a foot in width. Back of this narrow part was an unfilled, cavelike recess which appeared to increase in width. It was not possible to enter this recess; but, since the producing horizon had been worked out before it was reached, it seems improbable that vertebrate remains exist there. Some of the fossil-producing layer was removed by quarrying before the fossils were discovered. How much cannot be determined. In the same quarry are other joints and fissures, some filled with clay and gravel; but none of these yielded vertebrate remains.

There was a definite arrangement of materials within the fissure (Fig. 3). Resting on the bottom of the platform between the two joints and carrying somewhat downward into the deeper fissures along each joint, was a layer of chert fragments in a fine clay base. The chert fragments are angular and could not have been carried far, although the layer gives every indication of being water-laid. These cherts are entirely similar to the Mississippian residual cherts present in places on the surface and are probably derived from rocks of this age. Overlying the chert gravel was a layer of fine, pure clay about 2 feet in thickness. This bed contained the vertebrate remains. It had no coarse material and made sharp contact with the chert layer. There is no indication that the clay horizon was water-laid. It was unstratified and varied irregularly in color and com-

position. Overlying the clay was a layer of gravel composed of fragments of Plattin limestone and varying from a few inches to several feet in thickness. It filled the fissure above the clay and was in contact with either the limestone or the travertine covering of the lime-

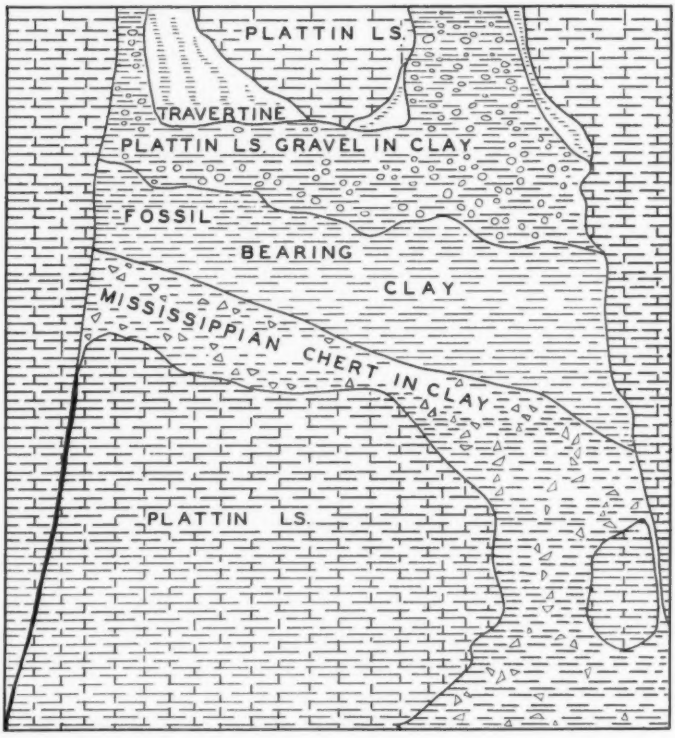


FIG. 3.—Diagrammatic sketch of fossil-bearing part of Herculaneum fissure, showing sequence of layers and relationships of the fill to the limestone.

stone. In places large pieces of travertine had fallen into the gravel and were covered by it.

The history of the development of the pocket was probably about as follows: Solution along joints in the Plattin limestone formed cavities which in places opened to the surface. Part of the surface

drainage was captured and flowed through the fissures and caves depositing gravel of Mississippian chert near the entrance. Some slight alteration in the surface drainage caused a cessation of the flow through this particular system, and there was a slow accumulation of clay. At this time small mammals and reptiles found the fissure habitable; and their remains, with remains of other animals which they carried in, were buried in the clay. Travertine deposits were being formed during this period and perhaps earlier. A subsequent change in drainage brought water back into the fissure, and gravel of Plattin limestone eventually filled the entrance.

TABLE 1

FAUNAL LIST

Reptilia:
- Chelonia
  - Indeterminate remains
- Squamata
  - Family Crotalidae
  - Family Colubridae
- Crocodilia
  - *Alligator?* sp.

Mammalia:
- Carnivora
  - Canidae
    - *Canis latrans* Say
    - *C. dirus* Leidy
    - *Urocyon* sp.
  - Procyonidae
    - *Procyon lotor* (Linnaeus)
  - Mustelidae
    - *Spilogale* cf. *interrupta* (Rafinesque)
  - Felidae
    - *Felis* cf. *concolor* Linn
- Xenarthra
  - Megalonychidae
    - *Megalonyx* cf. *jeffersoni* Desmarest
- Rodentia
  - Cricetidae
    - *Peromyscus* cf. *nuttalli* (Harlan)
    - *Neotoma pennsylvanica* Stone
    - *Microtus* cf. *ochrogaster* (Wagner)
  - Sciuridae
    - *Sciurus* sp.

Lagomorpha
  Leporidae
    Lepus americanus Erxleben
    Sylvilagus (*Limnolagus*) *aquaticus* (Bachman)
Perissodactyla
  Equidae
    Equus complicatus Leidy
    Equus sp.
  Tapiridae
    Tapirella cf. *bairdi* (Gill)
Artiodactyla
  Camelidae
    Tanupolama parvus n. sp.
  Cervidae
    Odocoileus virginianus (Boddaert)
  Bovidae
    Bison sp.
  Tayassuidae
    Mylohyus sp.

ENVIRONMENT OF THE FAUNA

The assemblage from this fissure almost certainly does not represent a complete cross section of the fauna of the region at the time the fissure was open to the surface, but it does give a clear picture of the types which were present. Five genera of mammals which occurred in the deposit are absent from the surrounding country today, while the remaining genera either exist there or have been in the region during the recorded history of man. The five genera no longer present are: *Equus* (except as introduced by man), *Tapirella*, *Tanupolama*, *Megalonyx*, and *Mylohyus*. *Bison* might also be included in this list, for, though the environment of today is not particularly suitable for it, it has recently existed in the general vicinity. Nineteen per cent of the genera are extinct, and 81 per cent are living today; but only 68 per cent are present in the area, *Equus* and *Tapirella* occurring in natural habitat elsewhere in the world. Of the living genera, only one species, *Canis dirus*, of those which can be definitely identified is extinct. A number of species cannot be assigned to living species because of the nature of the material, but there is no reason to believe that the differences which any of them show are of more than subspecific value.

The preponderance of living genera and species might imply an environment not greatly different from that of today. The extinct genera and those now existing elsewhere, however, throw a somewhat different light on the problem. *Equus* and *Bison* suggest a less wooded country, although the wood bison might exist under conditions not greatly different from those of today. *Tapirella*, *Mylohyus*, and *Megalonyx* would indicate a wooded country, warm climate, and considerable moisture. The alligator substantiates such a hypothesis. It is apparent that the assemblage is not one to be expected from any single set of conditions. Two explanations of its accumulation seem possible. The fissure might have been open for considerable time, during which radical changes in the climate occurred and different faunas lived in the area; or the deposit may have received the remains of forms living in two different but adjacent environments.

The distribution of the fossils within the deposit indicates that the animals were essentially contemporaneous. The clay horizon showed no sequence of faunas whatsoever. *Equus* teeth occurred throughout, as did the teeth of *Odocoileus*, *Lepus*, and all forms of which enough specimens were found to allow determination of their distribution in the clay. One alligator scute was found at the bottom of the clay, and another at the top. If there were any indication of water action in the clay, it might be assumed that there had been reworking; but the fact that even the finest structures show no water wear and that the clay had absolutely no pebbles or gravel in it appears to rule out such a possibility.

The nature of accumulation of material may have some bearing on the problem. The fissure at the locality in which the teeth occur is too small to permit the entrance of any of the larger animals, such as *Megalonyx*, *Equus*, *Bison*, or the large carnivores. The absence of any large bones and the small opening of the fissure upward preclude the possibility of trapping. It seems quite certain that the vertebrate material was carried in by some small animal, probably *Neotoma*, the wood rat. This is by far the most abundant form, except for the rabbit; and small carnivores, which conceivably might have carried in material, are rare. Also, the small number of bones in proportion to the number of teeth, under conditions in which bones were well preserved, is suggestive of the action of rodents rather than of

carnivores. The larger teeth would not be carried in by small carnivores. Confirming this opinion is the fact that every piece of bone and many of the larger teeth have been gnawed by rodents.

With this method of accumulation it appears possible for material from more than one type of environment to be assembled. A means of bringing together animals from open grasslands and woods is necessary. A water hole or stream near the boundary of two such areas might have accomplished this. Also, it would explain the presence of such water-living forms as the alligator. In all probability some such process as that suggested in the preceding paragraphs accounts for the rather odd assemblage occurring in this particular fissure.

CORRELATION

There is, at present, no general agreement as to the bases to be used in the correlation of Pleistocene faunas. Recent work has contributed much support to the idea that many of the genera once considered to be characteristic of the early Pleistocene actually existed into late or even post-Pleistocene times and that extinction of various genera and species was by no means contemporaneous over the whole country. The most concise statements of these principles are given by Romer[1] and Simpson.[2]

Much of the fauna of the Herculaneum fissure is modern in aspect. As pointed out previously, only three of the genera are extinct, and two exist elsewhere today. Eleven species of mammals are so close to living species that no differences are discernible in the teeth preserved. Three more species—those of *Urocyon*, *Sciurus*, and *Bison*—show no differences from modern species; but the particular teeth or the state of preservation, as the case may be, make assignment to any particular species unwise. Six species of mammals are entirely extinct: *Equus complicatus*, *Equus* sp., *Tanupolama parvus*, *Canis dirus*, *Mylohyus* sp., and *Megalonyx* cf. *jeffersoni*.

The preponderance of living species and genera would seem to imply a late or even post-Pleistocene age for the deposit. If, how-

[1] A. S. Romer, "Pleistocene Vertebrates and Their Bearing on the Problem of Human Antiquity," *The American Aborigines*, ed. D. Jenness (Toronto: University of Toronto Press, 1933), pp. 49–83.

[2] G. G. Simpson, "Pleistocene Mammalian Fauna of the Seminole Field, Pinellas County, Florida," *Bull. Amer. Mus. Nat. Hist.*, Vol. LVI (1929), pp. 561–600.

ever, the dictates of Hay be followed, *Equus*, *Tapirella*, and *Tanupolama* place the age as Early or, at the latest, Middle Pleistocene. The evidence of Romer, Simpson, and others appears sufficient to indicate that these forms existed much later than the limits set by Hay. Simpson suggests that their survival in Florida may be the result of a continuance of suitable conditions in Florida longer than in more northern parts of the country. This may be a factor, but there is also much evidence that in some northern regions forms which Hay considered to have become extinct in the Lower or Middle Pleistocene have existed well past these times.

The modern aspect of much of the Herculaneum fauna and the known cases of persistence of now extinct forms into relatively recent times in various parts of North America lead to the conclusion that this fauna is late Pleistocene or possibly even post-Pleistocene. Because of its relatively northerly position, it is to be considered not as a relic fauna but as one typical of the southeastern United States at the time of its accumulation.

Description of the Fauna

Class Reptilia

Order Chelonia

Various small fragments of bony carapace and plastron occurred throughout the deposit. None is sufficiently large to permit further identification.

Order Squamata

Suborder Ophidia

Family Crotalidae

A number of large vertebrae belong to this family. They appear to belong to a large species of the genus *Crotalus* but might possibly belong to another genus of the family.

Family Colubridae

Many vertebrae of snakes of this family occurred in the deposits. There is a considerable range in size, and some differences in characters. More than one genus may be present. Most of the vertebrae appear to belong to the genus *Coluber*, and some possibly to the genus *Elaphe*.

ORDER CROCODILIA

FAMILY CROCODILIDAE

Alligator? SP.

Three well-preserved scutes from the median-back series represent the remains of crocodilids found. As far as can be determined, they belong to the genus *Alligator*, and they do not differ from scutes of *A. mississippiensis*. The material is scant and not sufficiently diagnostic for definite assignment.

Class Mammalia

ORDER CARNIVORA

FAMILY CANIDAE

Canis latrans SAY

The coyote is represented by a single right lower carnassial tooth (Walker Mus. 1738). Although the tooth is somewhat larger than the corresponding tooth in many living coyotes, it is equaled by that

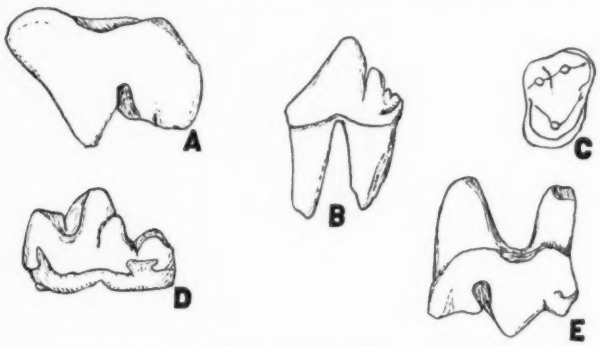


FIG. 4.—Teeth of carnivores from Herculaneum fissure. *A*, *B*, and *C*, *Canus dirus* (Walker Mus. 1736). *A*, P^4; *B*, P_4; *C*, M^2. *D*, *C. latrans*, M_1 (Walker Mus. 1738). *E*, *Felis* cf. *concolor*, P^4 (Walker Mus. 1737). × 1.

in some of the northern representatives of the species to which it has been referred. The crown pattern is identical with that of *C. latrans*.

Canis dirus LEIDY

Three teeth, probably belonging to different individuals, belong to a large species of *Canis* and cannot be differentiated from *C. dirus*. A right P^4 and P_4 and a left M^2 comprise the material referred to this

species (Walker Mus. 1736). In addition there are two canine teeth, which probably belong to the same species.

In size, the teeth from Herculaneum fall very close to those from the tar pits of California, usually called *C. dirus*. In crown pattern no differences are apparent unless it be in the protocone of P^4, which is damaged on the Herculaneum specimen and might have been slightly smaller than that on the California forms. P_4 apparently belonged to a slightly smaller individual than did the other two.

TABLE 2

MEASUREMENTS (AND COMPARISONS WITH *C. dirus* OF CALIFORNIA)

		C. dirus Herculaneum (Walker Mus. 1736)	*C. dirus* California (Walker Mus. 1344)	*C. dirus* California (Walker Mus. 397)
P_4	Anteroposterior	18.0 mm.	20.0 mm.	20.5 mm.
	Transverse	9.2	10.2	10.2
P^4	Anteroposterior	31.0	28.5	31.0
	Transverse	14.2	14.3	14.1
M^2	Anteroposterior	15.2	15.0	15.2
	Transverse	10.9	10.4	11.9

A number of large wolves from the southeastern part of the United States have been referred to Sellard's species, *C. ayersi*. There is no good dental character separating *C. dirus* and *C. ayersi*. Sellards[3] reports minor differences, the only one of which is applicable in this case being a reduction of the protocone of P^4 of *C. ayersi*. There is considerable variation in the size of this cone in the specimens referred to *C. dirus*. The main differences between the two are in skull proportions. Although the type of *C. dirus* comes from Evansville, Indiana, the West Coast forms have been referred to the species. Since the type consists only of a maxillary and teeth P^2–M^1, the skull proportions are unknown, and it is not actually possible to tell whether the specimen is closer to the West Coast forms or to the Florida forms which have been called *C. ayersi*. Sellards, realizing this but feeling that usage had established the West Coast forms as

[3] E. H. Sellards, *Fla. Geol. Surv. 8th Ann. Rept.* (1916), pp. 152–57.

C. dirus, preferred to assign the Florida forms to a new species, admitting the possibility that they actually might be the same as the type of *C. dirus*. Strict application of the rules of taxonomic procedure makes such an assignment somewhat dubious; but certainly much less confusion has arisen to date than would have been the case had he chosen the other course and proposed a new specific name for the West Coast forms when there is no certainty that they are not *C. dirus* and that the Florida forms are. Until such time as a new and more complete specimen of *C. dirus* is obtained from the type locality—and it is very doubtful that such a time will ever arrive—this question cannot be definitely settled. It seems best to accept Sellards' species and to continue to call the West Coast forms *C. dirus* unless the contrary is found to be the case. Because of the geographical positions of the specimens in question, it seems more probable that the Florida and Indiana forms will prove to be similar and the Indiana and California forms different. Hence, in accepting Sellards' species, it must be remembered that it is a matter of convenience rather than an established difference upon which the species rests.

The specimens from Herculaneum lie closer geographically to the type of *C. dirus* than to either the West Coast *C. dirus* or to the Florida *C. ayersi*. There are no morphological characters which indicate assignment to one species or the other. Purely on the basis of locality, the specimens are assigned to *C. dirus*, keeping in mind that they may be identical with the Florida forms and at the same time with the type of *C. dirus*.

Urocyon SP.

Only one tooth representing this genus was found. It is P_4 and lacks any characters which might permit specific assignment. It is readily differentiated from *Vulpes* by the heavy development of the cingulum. The tooth falls closer to the corresponding tooth in some specimens of *U. cinereoargentus* than to those of other species of *Urocyon*.

FAMILY PROCYONIDAE

Procyon lotor (LINNAEUS)

This genus is represented by a single lower left carnassial tooth which is indistinguishable from the corresponding tooth in the common North American species *P. lotor*.

FAMILY MUSTELIDAE

Spilogale CF. *interrupta* (RAFINESQUE)

This genus is represented by a part of the ramus of the right lower jaw containing the carnassial tooth and the alveolus of M_2. Comparison with the various species and subspecies of the genus shows that the specimen is very close to the subspecies of *S. interrupta* which is common in Oklahoma and Kansas. The carnassial is slightly shorter than in the average *S. interrupta*, and the anterior part of the blade is inflected inward. These are characters found in many individuals of *S. interrupta* from Oklahoma and Kansas.

FAMILY FELIDAE

Felis CF. *concolor* LINNAEUS

The felids are very poorly represented in the collection from Herculaneum. One right, upper carnassial tooth of a mountain lion (Walker Mus. 1737) is the only specimen which can be identified as belonging to this family. The tooth is of the same dimensions as the corresponding tooth of *F. concolor*. A small cusp on the externo-anterior slope of the parastyle is strongly developed. This character is seldom present in members of the genus *Felis* but is usually well developed in *Lynx*. In *F. concolor*, however, the development of the cusp is variable, and in some individuals it is as strong as in the fossil tooth. The size of the tooth excludes it from *Lynx*.

TABLE 3

MEASUREMENTS

	Mm.
Anteroposterior	23.6
Transverse	11.3

ORDER XENARTHRA

FAMILY MEGALONYCHIDAE

Megalonyx CF. *jeffersoni* DESMAREST

Four cheek teeth of the ground sloth comprise the edentate material derived from the fissure (Walker Mus. 1738). That they belong to the genus *Megalonyx* is certain. There are no diagnostic features which separate them from *M. jeffersoni*, but the material is not sufficient for certain specific identification.

Order Rodentia

Rodents of a number of types were very abundant in the fissure. Isolated teeth were most abundant; but some jaws with teeth, partial skulls, limb bones, and vertebrae also were found. Wood rats and rabbits far outnumber the other types in the collection.

Family Cricetidae

Peromyscus cf. *nuttalli* (Harlan)

Several teeth of this small rodent were recovered. Best preserved is M_1 of the right side (Walker Mus. 1739). In pattern the tooth is in perfect accord with the corresponding tooth in the living *P. nuttalli*, which occurs in the same region. The size is somewhat greater than that of any specimen of this species studied, a character found to be constant in all the teeth of this genus which were recovered. The difference might be considered specific if the fossil material were sufficient to warrant the erection of a new species. For the present it is advisable to consider the specimens as representing a large variety of *P. nuttalli*.

Neotoma pennsylvanica Stone

Many cheek teeth and incisors of the species occurred throughout the deposit. A set selected for study includes representatives of all the upper and lower cheek teeth (Walker Mus. 1740). The crown patterns are identical with those of recent specimens of *N. pennsylvanica*, and the size range of the fossils falls well within the limits of the species.

Microtus cf. *ochrogastor* (Wagner)

Teeth of this genus were rare in the deposit, and perhaps some were overlooked because of their very small size. For comparative purposes M_1 was found to be the most useful (Walker Mus. 1741). This molar is composed of a posterior loop, five alternating triangles, and an anterior loop and corresponds closely with the pattern of M_1 in recent specimens of *M. ochrogastor*. The tooth may be distinguished from that of *M. pennsylvanicus* readily, for in the latter a deep sulcus on the lingual surface of the anterior loop results in a partial formation of a sixth triangle. This sulcus is poorly developed or absent in the recent specimens of *M. ochrogastor* examined, and is

but faintly visible in the fossil forms. Other teeth are less diagnostic of the species but correspond very closely to comparable teeth in *M. ochrogastor*.

FAMILY SCIURIDAE

Sciurus SP.

A single molar tooth of this genus was found. The very small size may account in part for the apparent scarceness of the squirrels. There can be no doubt that the one tooth found belongs to the genus *Sciurus*, but specific identification is out of the question.

ORDER LAGOMORPHA

The rabbits were about as abundant as the wood rats. Most specimens consisted of isolated teeth; but a number of associated series of cheek teeth, one partial skull, and limb bones were found.

FAMILY LEPORIDAE

Lepus americanus ERXLEBEN

This genus is represented by many teeth, including associated series, a partial skull, and a number of limb bones (Walker Mus. 1742). Both upper and lower teeth compare in all respects with those of the recent *L. americanus*.

Sylvilagus (*Limnolagus*) *aquaticus* (BACHMAN)

This rabbit is represented by two P_3's, one with P_4 associated, and possibly by a few large molar teeth. The two lower premolars are the largest rabbit teeth in the collection. The crown is more quadrilateral in cross section than is the case in teeth of other genera and species. The anterior margins are marked by more than two well-defined re-entrant angles, three in Walker Mus. 1743 (Fig. 5) and four in Walker Mus. 1744. These characters are recognized as being diagnostic of the genus *Limnolagus* by Lyon.[4] In addition, he points out a number of characters of skull and skeleton which lead him to conclude that *Limnolagus*, although proposed by Mearns[5] to supplant the preoccupied *Hydrolagus* as a subgenus of *Lepus*, is sufficiently distinct from other lagomorphs to constitute a separate genus. The species included by Lyon in *Limnolagus* are: *L. aquati-*

[4] M. W. Lyon, "Classification of the Hares and Their Allies," *Smith. Misc. Coll.*, Vol. XLV (1903), pp. 321–447.

[5] E. A. Mearns, "A New Subgeneric Name for the Water Hares (*Hydrolagus*, Grey)," *Science*, Vol. V (1897), p. 393.

cus (Bachman), *L. palustris* (Bachman), and *L. telmalemonus* (Elliot).

Most recent workers have considered these species as members of the genus *Sylvilagus*. That the group forms a distinct branch of *Sylvilagus* is clearly recognized, but that it is sufficiently different from other groups of the genus to be considered as a separate generic group is open to question. It seems best to refer the swamp rabbits to the genus *Sylvilagus* and the subgenus *Limnolagus*.

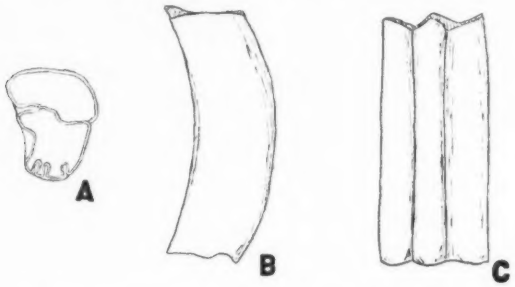


FIG. 5.—*Sylvilagus* (*Limnolagus*) *aquaticus* (Walker Mus. 1734), P_3, *A*, crown; *B*, posterior; *C*, lateral. × 4.

The fossil teeth may be referred with confidence to *S. aquaticus*. Although the teeth show some variation in marginal development, they lie well within the range of variation of recent representatives of the species.

TABLE 4

MEASUREMENTS

	Walker Mus. 1743	Walker Mus. 1744
Anteroposterior	4.1 mm.	4.0 mm.
Transverse	3.0	3.1

ORDER PERISSODACTYLA

FAMILY EQUIDAE

Equus complicatus LEIDY

Teeth of this large horse were common in the deposit, outnumbering any of the other larger teeth. A considerable number of upper

and lower cheek teeth and incisors were obtained (Walker Mus. 1745).

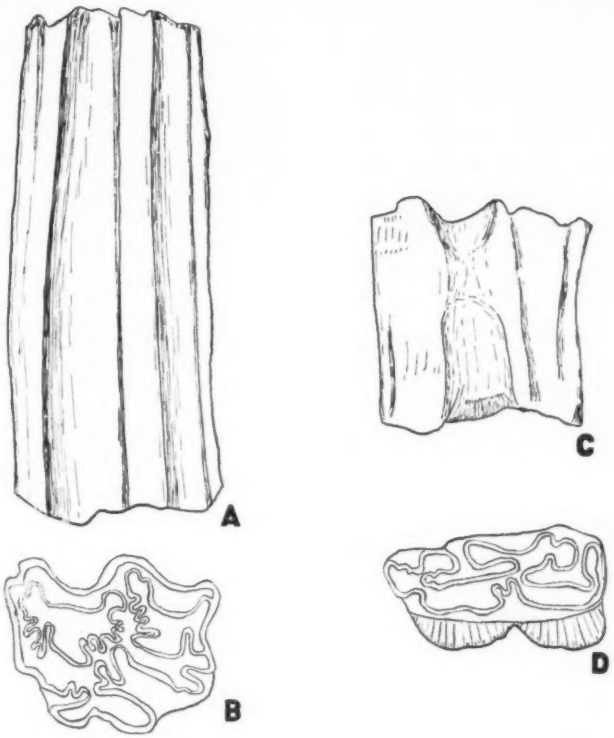


FIG. 6.—*Equus complicatus* (Walker Mus. 1745). *A* and *B*, upper molar; *C* and *D*, lower molar. × 1.

Equus SP.

Two teeth of a smaller horse represent a second species of *Equus* found in the deposit. Although these teeth appear to be specifically distinct from those of any well-known Pleistocene horse, it seems unwise to erect a new species on the basis of two teeth in a genus which even now has sufficient contemporary species recorded to tax the imagination.

One upper and one lower cheek tooth clearly belong to this species. Other less well-preserved teeth and parts of teeth may be less certainly referred to it. The principal characters of the species

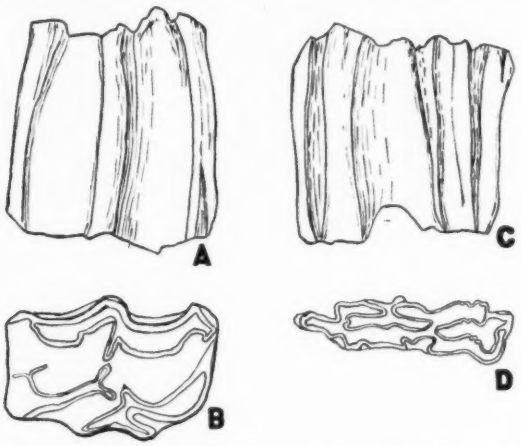


FIG. 7.—*Equus* sp. (Walker Mus. 1746). *A* and *B*, upper molar; *C* and *D*, lower molar. × 1.

are: (1) the anteroposterior dimension of the teeth is very great in proportion to the transverse dimension; (2) the enamel pattern is simple, not complicated by plications; and (3) the various cusps are much elongated in the anteroposterior plane.

TABLE 5

MEASUREMENTS

	Upper Molar (Walker Mus. 1746)	Lower Molar (M_3) (Walker Mus. 1746)
Anteroposterior	34.3 mm.	33.6 mm.
Transverse (max.)	20.5	9.1

FAMILY TAPIRIDAE

Tapirella CF. *bairdi* (GILL)

This genus is represented by one very well-preserved, unworn M^2 (Walker Mus. 1747). In the course of the study of this specimen all

the skulls of the extensive collection of tapirs in the Field Museum of Natural History were examined. These studies leave no doubt that the tooth in the Herculaneum collection belongs to the genus *Tapirella* and not to the genus *Tapirus*, to which Pleistocene tapirs have generally been referred.

The most important character of M^2 which can be used to differentiate *Tapirella* from *Tapirus* is the continuous nature of the ectoloph, which passes as a ridge from the paracone to the metacone with but slight deviation from the level of its inception on the paracone. In *Tapirus* this loph slopes sharply down from the para-

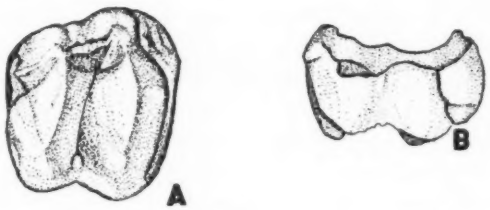


FIG. 8.—*Tapirella* cf. *bairdi*, M^2 (Walker Mus. 1747). *A*, crown; *B*, external. × 1

cone and creates a distinct V between itself and the metacone. This difference is manifest in the other molars of the upper dentition but is best shown on M^2. A second character, which is useful but not so diagnostic, because extreme members of the two genera approach each other in it, is that the posterior cingulum of *Tapirella* is less well developed than that in *Tapirus*. In unworn teeth of *Tapirella* the crests of the lophs and cinguli are rugose, while in *Tapirus* they are smooth.

The fossil tooth from Herculaneum corresponds to *Tapirella* in these characters. The pattern is that of *Tapirella bairdi*, but the tooth is somewhat larger than the corresponding molar in any specimen of *Tapirella bairdi* encountered in these studies. It may represent an undescribed species; but, since there are no clearly diagnostic features, it is tentatively referred to *Tapirella bairdi* until such time as more adequate material may prove otherwise.

Specimens of Pleistocene tapirs found in North America have been referred quite generally to the genus *Tapirus*. Most of the specimens consist only of dentition, and usually only of partial dentition. In certain cases reference to the genus *Tapirus* is clearly correct. *Tapirus veroensis* Sellards[6] clearly is a member of the genus, as is *T. veroensis sellardsi* Simpson.[7] *Tapirus haysii* Leidy, to which many of the Pleistocene tapirs have been referred, is not clearly assignable to one genus or the other on the basis of figures of the type,[8] and it is doubtful that the worn dentition will ever permit actual placement. Probably belonging to *Tapirus* rather than to *Tapirella* is *Tapirus*

TABLE 6

MEASUREMENTS

	Mm.
Anteroposterior	25.7
Transverse	31.1

tennesseae Hay.[9] From the figures and descriptions it seems to be rather far removed from any other tapir, but the characters of the upper dentition are those of *Tapirus* rather than *Tapirella*.

In his description of two tapirs from the West Coast Merriam[10] referred a specimen from the auriferous gravels of California to *Tapirus haysii californicus* and one from Cape Blanco, Oregon, to *Tapirus* near *haysii californicus*. Although he referred these specimens to *Tapirus*, Merriam said, in writing of both specimens: "Both represent species not distinctly removed from the existing *Tapirus* (*Elasmognathus*) *bairdi*." Palmer, in 1903, proposed the name *Tapirella* to supplant *Elasmognathus*, which was preoccupied. This genus is generally recognized now as being distinct from

[6] "The Skull of a Pleistocene Tapir, etc.," *Fla. Geol. Surv. 10th and 11th Ann. Repts.* (1918), pp. 57–76.

[7] Simpson, *op. cit.*, pp. 586–89.

[8] F. S. Holmes, *Post Pleiocene Fossils of South Carolina* (Charleston: Russell & Jones, 1860), Nos. 8, 9, and 10.

[9] O. P. Hay, "Descriptions of Some Pleistocene Vertebrates Found in the United States," *Proc. U.S. Nat. Mus.*, Vol. LVIII (1921), pp. 83–146.

[10] J. C. Merriam, "Tapir Remains from Late Cenozoic Beds of the Pacific Coast Region," *Univ. Calif. Pub. in Geol.*, Vol. VII (1913), pp. 169–75.

Tapirus. Merriam apparently considered *Elasmognathus* (he did not recognize the change of name to *Tapirella*) as a subgenus of *Tapirus*. Thus, in suggesting a relationship of his West Coast specimens to *Tapirus haysii* and to *Tapirus* (*Elasmognathus*) *bairdi*, Merriam implies that *Tapirus haysii* is actually close to *Tapirella*. If *Tapirella* is considered as a distinct genus, for which there seems to be adequate justification, the West Coast forms, both on the basis of Merriam's opinion and on the basis of his descriptions, should be referred to this genus, perhaps with tentative reference to *Tapirella bairdi*. This does not alter the indeterminate position of *Tapirus*

TABLE 7

Tapirus
  Tapirus veroensis Sellards
  Tapirus veroensis sellardsi Simpson
  Tapirus tennesseae Hay
Tapirella
  Tapirus haysii californicus Merriam
  Tapirus near *haysii californicus* Merriam
  Tapirella cf. *bairdi* (this paper)
Indeterminate
  Tapirus haysii Leidy*

*In reference to type specimen only, not to referred specimens.

haysii, since the type, as stated above, is inadequate for determination.

A number of specimens of tapirs from the Pleistocene have been referred to *Tapirus haysii*, partly on the basis of size, partly because there were no differences visible between the dentitions of the type and the referred specimens, and partly because this species has gained considerable prominence as the common Pleistocene tapir. Because of the nature of the type specimen, specific identity in these cases must be open to some question. One of the best specimens referred to *Tapirus haysii* is that of Stovall and Johnson[11] from Chickasha, Oklahoma. The authors state that the form is very similar to *Elasmognathus bairdi*, not recognizing the change of generic

[11] J. W. Stovall and C. S. Johnson, "*Tapirus haysii* from Oklahoma," *Amer. Mid. Nat.*, Vol. XV (1934), pp. 92–93.

name, but identify it as *Tapirus haysii*. The photograph shows a dentition which appears to be closer to *Tapirus* than to *Tapirella*, but the characters are not well enough shown to make this conclusion certain.

A careful restudy of the North American tapirs is needed. This can be done only by an examination of the type material and comparisons of referred specimens and should be done with the understanding of the distinct differences between *Tapirus* and *Tapirella*.

Without access to much of the type material and the specimens referred to the various species, it appears that the various tapirs of the Pleistocene should be classified as tabulated.

ORDER ARTIODACTYLA

FAMILY CAMELIDAE

Tanupolama parvus N. SP.

Holotype.—A well-preserved M^2 (Walker Mus. 1735).

Horizon and locality.—Late Pleistocene near Herculaneum, Missouri.

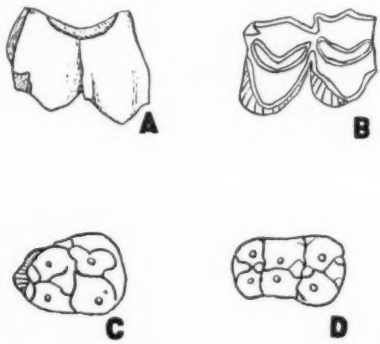


FIG. 9.—*A* and *B*, *Tanupolama parvus* n. sp., M^2. *A*, external; *B*, crown. *C* and *D*, *Mylohyus* sp. *C*, crown of molar; *D*, crown of desciduous P_4. × 1.

Diagnosis.—About one-fourth smaller than any previously described species of this genus. External enamel surface of M^2 very little folded. Parastyle and mesostyle poorly developed.

The single tooth is clearly referable to the genus *Tanupolama* but

is specifically distinct from *T. stevensi* Stock[12] and *T. mirifica* Simpson.[13] In discussing the genus *Tanupolama*, Stock states: "The superior molars likewise exhibit less pronounced folding of the external enamel surface and the parastyle and metastyle appear to be less prominent in these teeth than in the comparable teeth of the living species." These characters occur in the specimen from Herculaneum but are even more clearly shown than in *T. stevensi*. *T. mirifica* has the styles better developed than *T. stevensi*. As in *T. mirifica*, the anterior lobe of *T. parvus* is considerably wider basally than the posterior lobe.

TABLE 8

MEASUREMENTS

	T. parvus (Walker Mus. 1735)	(M^3) *T. mirifica*	(M^3) *T. stevensi*
Anteroposterior	19.7 mm.	24 mm. (approx.)	23.9–29.7 mm.
Transverse	14.5	18 (approx.)	17.0–25.3

The presence of this genus in Missouri considerably extends the range of the group. It is felt that, as a general rule, it is unwise to describe a new species on the basis of a single tooth. In this case, however, where the form is removed geographically from any other known representative and where the characters are distinct and diagnostic, it seems best to designate a new species, as has been done.

FAMILY CERVIDAE

Odocoileus virginianus (BODDAERT)

Teeth of this deer are the most abundant mammalian remains obtained from the Herculaneum fissure except for the wood rats and rabbits. Representatives of all lower and upper molars and premolars were obtained. A few jaw fragments bearing one or more teeth were recovered. There are no characters in the teeth which separate them from *O. virginianus*, and they may be referred to this genus and species with complete confidence.

[12] C. Stock, "*Tanupolama*, a New Genus of Llama from the Pleistocene of California," *Carnegie Inst. Wash. Pub. 393* (1928), pp. 31–39.

[13] Simpson, *op. cit.*, pp. 593–96.

FAMILY BOVIDAE

Bison SP.

Five teeth of *Bison* were obtained. They are not sufficient for specific determination but are of interest in showing the presence of this large bovid in the region of the fissure.

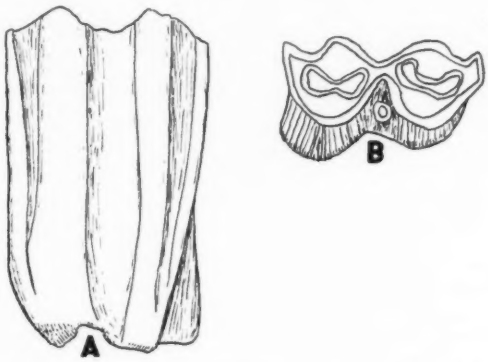


FIG. 10.—*Bison* sp. Lower molar. (Walker Mus. 1749.) *A*, external; *B*, crown. × 1

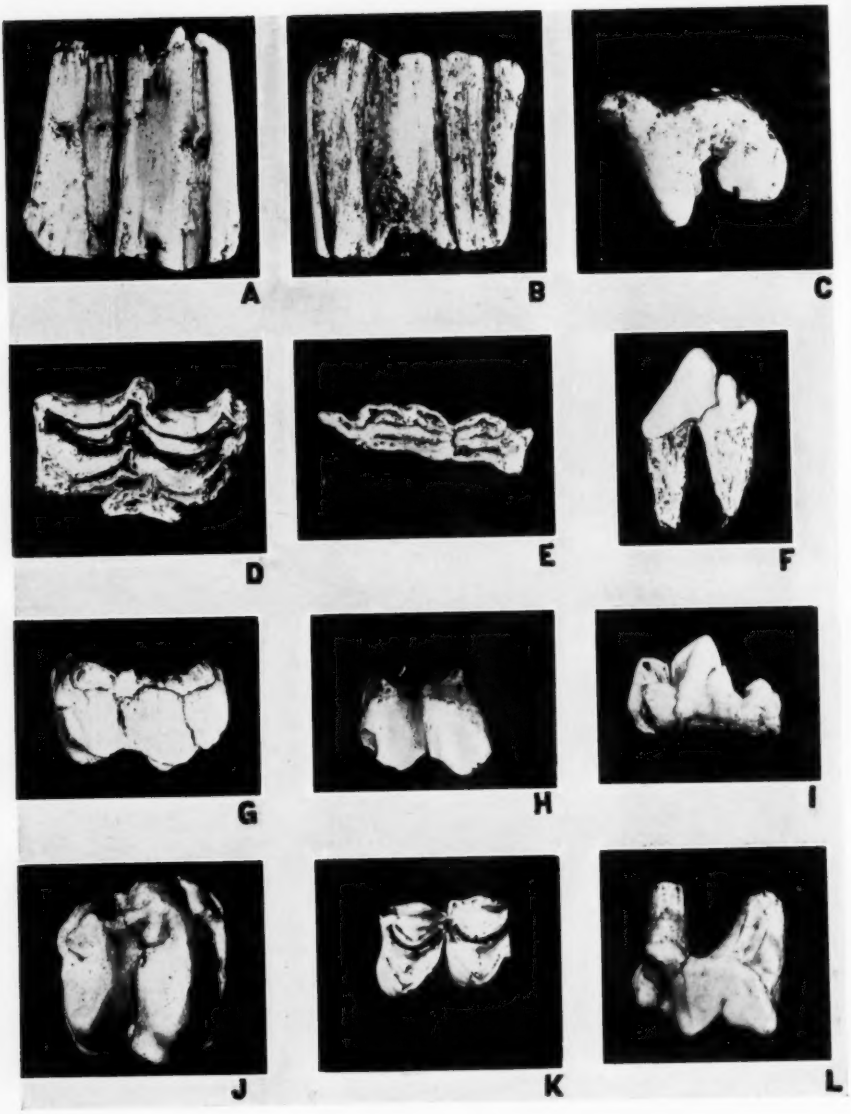
FAMILY TAYASSUIDAE

Mylohyus SP.

Two complete cheek teeth and a fragment of a third comprise all the material of this genus which was recovered. Specific identification is not possible on the basis of the two well-preserved teeth. Of some interest is one of the two cheek teeth, an unworn milk P_4. Its characters are shown in Figure 9.

ACKNOWLEDGMENTS.—I am much indebted to Mr. Jenni for bringing this deposit to my notice and for his aid and hospitality during our stay in the field. I also wish to express my appreciation to the department of zoölogy of the Field Museum of Natural History of Chicago for its co-operation in permitting me free use of its extensive osteological collections and to Mr. Paul O. McGrew, of the department of paleontology of the same institution, for his aid in the preparation of this paper. Mr. Read's assistance in the field and in the preparation of the manuscript has been of great value.

PLATE I



EXPLANATION OF PLATE I

Photographs of selected mammal teeth from the Herculaneum fissure. Natural size.

A. *Equus* sp. (Walker Mus. 1746). Upper molar, external.
B. *Equus* sp. (Walker Mus. 1746). Lower molar, external.
C. *Canis dirus* (Walker Mus. 1736). Upper carnassial.
D. *Equus* sp. (Walker Mus. 1746). Upper molar crown.
E. *Equus* sp. (Walker Mus. 1746). Lower molar, crown.
F. *C. dirus* (Walker Mus. 1736). P_4.
G. *Tapirella* cf. *bairdi* (Walker Mus. 1747). M^2, external.
H. *Tanupolama parvus* n. sp. (Walker Mus. 1735). M^2, external.
I. *C. latrans* (Walker Mus. 1738). M_1.
J. *T.* cf. *bairdi* (Walker Mus. 1747). M^2, crown.
K. *T. parvus* n. sp. (Walker Mus. 1735). M^2, crown.
L. *Felis* cf. *concolor* (Walker Mus. 1737). P_4.

PRE-CAMBRIAN CRYSTALLINE ROCKS OF NORTH-CENTRAL UTAH

A. J. EARDLEY AND R. A. HATCH
University of Michigan

ABSTRACT

Four classes of rocks are recognized, namely: metamorphic sedimentary rocks, metamorphic silicic igneous rocks, injection gneisses, and metamorphic mafic rocks. The sedimentary rocks are now metaquartzites, quartz schists, arkosites, conglomerate schists, and possibly metamorphosed graywackes. The pebbles in the quartz-chlorite conglomerate schist were definitely derived from a pre-existing siltstone, and the metaquartzites may possibly represent older sediments that have been re-worked. Other rocks such as the arkosites were probably derived directly from some near-by pre-existing igneous rock.

After sediments of considerable thickness were deposited they were thoroughly injected by sills and dikes and also intruded by a few small stocks. The igneous material consists of granite, quartz monzonite, and pegmatite. The injection occurred during a prolonged orogeny which resulted in widespread development of foliation and various cataclastic structures.

The recrystallization, cataclastic features, and mineral composition of the Farmington Canyon complex, as the ancient crystalline rocks are here designated, indicate that the metamorphism was of the low- to medium-grade dynamic type. This main period of metamorphism occurred in early or Middle pre-Cambrian time and was more intense than any deformation since. Later crustal disturbances affected very little the structures left in the rocks by this early metamorphism, except locally in fault zones.

INTRODUCTION

LOCALITIES OF EXPOSURE

The localities treated under the title "north-central Utah" are Antelope Island in Great Salt Lake and the Wasatch Mountains. The local areas where pre-Cambrian crystalline rocks are exposed are shown on the map (Fig. 1). The pre-Cambrian rocks of the Grouse Creek Mountains in the northwest corner of the state have not been studied and are not included in the discussion.

MAJOR DIVISIONS OF ROCKS

The major divisions of pre-Cambrian rocks in north-central Utah are an ancient series of crystalline gneisses, schists, granites, and pegmatites, and a younger series of quartzites, phyllites, shales, slates, tillites, and limestones. Both divisions have an exposed thickness

greater than 10,000 feet and are separated from each other by a profound unconformity. The present paper deals with the older

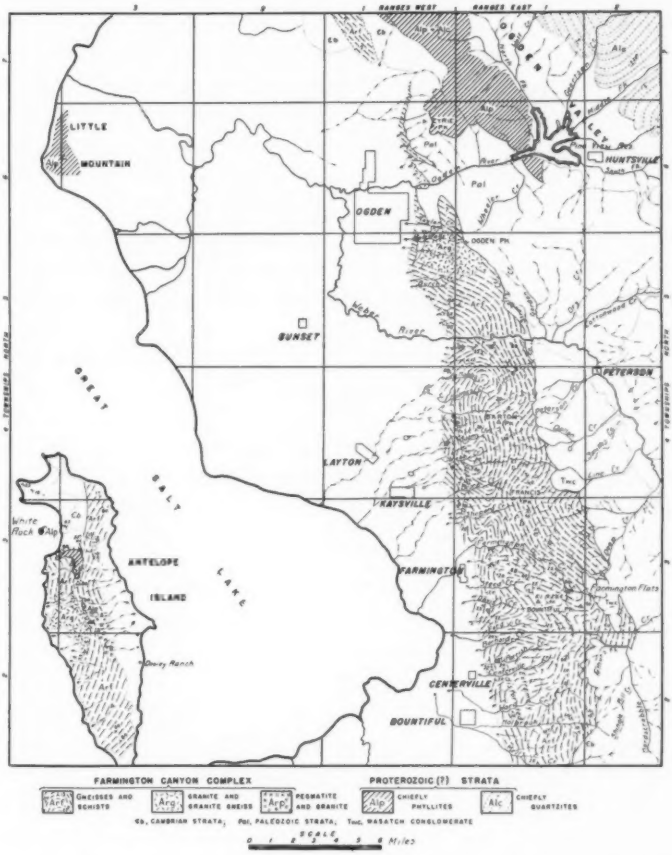


Fig. 1.—Geologic map of north-central Utah showing the pre-Cambrian rocks of the Bountiful-Ogden section of the Wasatch Mountains and of Antelope Island.

underlying crystalline rocks. The overlying stratified rocks, presumably of Proterozoic age, will be treated in another report.

PREVIOUS WORK

The pre-Cambrian crystalline rocks were first observed by Captain Stansbury in 1849,[1] and then by King, Emmons, and Hague[2] in the late seventies.

Butler, Loughlin, and Calkins[3] in 1920 contributed to the knowledge of the pre-Cambrian rocks of Utah by several petrographic descriptions of granites and associated Archean crystalline rocks in local mining districts. Schneider[4] in 1925 noted differences in the gneisses and schists exposed between Big and Little Cottonwood canyons and those north of City Creek Canyon. In 1930, east of Santaquin, Eardley[5] found an Archean complex, which includes a granite of pre-Algonkian age intrusive into the gneisses and schists. The Algonkian quartzite and shale beds are in turn overlain unconformably by the Cambrian quartzite.

Crawford[6] published a note on an Archean metaquartzite east of Bountiful in 1935, and in the same year, in a summary of the pre-Cambrian rocks of Utah and Wyoming Blackwelder[7] recognized two general divisions: the overlying "quartzite-slate system" and the underlying "metaquartzite and schist system." The older is the subject of the present paper.

PRESENT WORK

The largest area of the old crystalline rocks, the Bountiful-Ogden section of the Wasatch Range, was traversed thoroughly enough in the present study to map the foliation and to sample the most common rock types. The field work was not sufficient to delimit formations throughout the area of the crystalline rocks, and their

[1] H. Stansbury, "Exploration and Survey of the Valley of the Great Salt Lake of Utah, etc.," *U.S. 32nd Congr. Spec. Sess., S. Ex. Doc. 3* (1853).

[2] Clarence King, S. F. Emmons, and Arnold Hague, *Exploration, 40th Parallel, Rept.*, Vol. II (1877), p. 461.

[3] B. S. Butler, G. F. Loughlin, F. C. Calkins, and Others, "Ore Deposits of Utah," *U.S. Geol. Surv. Prof. Paper 111* (1920), pp. 222, 234, 324, etc.

[4] Hyrum Schneider, "A Discussion of Certain Geologic Features of the Wasatch Mountains," *Jour. Geol.*, Vol. XXXIII (1925), pp. 35–37.

[5] A. J. Eardley, "Stratigraphy of the Southern Wasatch Mountains, Utah," *Mich. Acad. Sci., Arts, Letters*, Vol. XVIII (1932), pp. 311–14.

[6] A. L. Crawford, "Archean Metaquartzites East of Bountiful, Utah," *Utah Acad. Sci.*, Vol. XII (1935), p. 167.

[7] Eliot Blackwelder, "Summary of the Pre-Cambrian Rocks of Utah and Wyoming," *Utah Acad. Sci.*, Vol. XII (1935), pp. 153–57.

structure and thickness are not yet accurately known. Additional information, however, has been obtained on the origin and metamorphic history of these thick and complex rocks and is presented in the following pages.

The field work was done by Eardley in the course of structural studies in the region and the petographic work by Hatch in the laboratories of the department of mineralogy of the University of Michigan.

NAME AND TYPE LOCALITY

The name "Farmington Canyon complex" is given to the great group of crystalline rocks in the north-central Utah area, and in the event that more detailed work in the future results in subdivision and correlation the type locality is specified as Farmington Canyon and Bountiful Peak (see Fig. 1 and "Classification and Nomenclature of Rock Units," by Geological Society of America Committee, *Bull. Geol. Soc Amer.*, Vol. XLIV [1935], p. 445).

STRUCTURE

The rocks of the Farmington Canyon complex are distinctly stratified throughout the region, and many reliable strike and dip readings were recorded. For the most part, the foliation is parallel to the bedding planes, and the abundant lit-par-lit injections are parallel to the general stratification.

Although the strikes and dips vary locally, the prevailing strike of the foliation and bedding is north to northwest. An open anticline trends about N. 60° W. through Bountiful Peak and is flanked on both sides by open synclines, all of which plunge about 15°–20° to the northwest (Fig. 1). The beds strike persistently to the northwest in Weber Canyon parallel to the axes of the folds of the Bountiful Peak area, and a thickness in excess of 10,000 feet is estimated to exist there. The structure between Weber Canyon and Farmington Canyon, along the new C.C.C. road from Bountiful to Bountiful Peak and from Shepard Creek north to Holmes Creek across the mouths of the canyons, is complex and was not studied in sufficient detail to allow satisfactory description.

A number of high-angle faults of small displacement were noted within the Farmington Canyon complex but their age could not be definitely determined. The western face of the Wasatch Range in

this section is a fault scarp of the Pliocene and Pleistocene Basin and Range deformation, and the small high-angle faults within the complex may be of the same age. Thrust faults resulting from east-west compression during the Laramide revolution[8] have been traced

TABLE 1

CLASSES OF ROCKS OF THE FARMINGTON CANYON COMPLEX STUDIED MICROSCOPICALLY

Group	Slide No.	Name of Rock	Location
Metamorphosed sedimentary rocks	5	Quartz-sericite schist	Bountiful Peak, NE. slope
	6	Quartz-chlorite schist	Bountiful Peak, NE. slope
	7	Arkosite	Bountiful Peak, E. slope
	12	Quartz-chlorite conglomerate schist	Bountiful Peak, E. slope
	11	Chloritic siltstone (pebble from 12)	Bountiful Peak, E. slope
	14	Arkosite	Antelope Island, near top highest peak
	30	Schistose quartzite	Bountiful Peak, E. slope
Metamorphosed silicic igneous rocks	1	Gneissic hornblende granite	Ogden Canyon, mouth of
	2	Mylonite granite gneiss	Bountiful Peak, E. slope
	3	Quartz aplite gneiss	Bountiful Peak, E. slope
	13	Feldspathic pegmatite	Antelope Island, SE. highest peak
	22	Gneissic granite	Ogden Canyon, mouth of
	23	Gneissic quartz monzonite	Antelope Island, W. highest peak
	27	Gneissic quartz monzonite	Waterfalls Canyon
Metamorphosed injection gneisses	9	Biotite injection gneiss	Bountiful Peak, E. slope
	10	Biotite injection gneiss	Bountiful Peak, E. slope
Metamorphosed mafic rocks	4	Hornblende-labradorite gneiss	Bountiful Peak, E. slope
	8	Hornblende-labradorite gneiss	Bountiful Peak, E. slope
	15	Epidote-chlorite schist	Farmington Flats, ridge, east of
	28	Chlorite-sericite schist	Waterfalls Canyon
	29	Hornblende gneiss	Antelope Island, near top highest peak

from Ogden Canyon southward into the schists and gneisses and are lost. The zone of distortion between Shepard and Holmes creeks may be a thrust fault of Laramide age.

[8] A. J. Eardley, "Structure of the Wasatch–Great Basin Region," *Bull. Geol. Soc. Amer.*, Vol. L (1939), Pl. I, and pp. 1285–89.

SUMMARY OF ROCK TYPES AND DISTRIBUTION

A petrographic study of twenty different rocks selected as representative of the important types found in the field has led the writers to divide them into four groups, as follows: the sedimentary rocks, the silicic igneous rocks, the injection gneisses, and the mafic rocks. Only the metamorphic equivalents of these rocks are now present. Table 1 classifies the various rock types studied and gives the localities from which the specimens came.

METAMORPHOSED SEDIMENTARY ROCKS

MEGASCOPIC FEATURES

The primary feature of the metamorphosed sediments is their stratification. This, together with their mineralogical composition, constitutes the best evidence for a sedimentary origin. Brief descriptions of the megascopic features of the more typical rocks of the group follow.

A quartz-sericite schist and a quartz-chlorite schist in two adjacent beds near Bountiful Peak are grayish-green in color, have a greasy luster, and have lost their original granular texture. An inconspicuous schistose structure is produced by shear planes and an abundance of platy chlorite (clinochlore) and sericite. Much of the quartz-sericite schist might be called metaquartzite on the basis of its megascopic appearance.

Another metaquartzite is very conspicuous and abundant along the new C.C.C. road from Bountiful to Bountiful Peak. It is white and is composed chiefly of quartz, although a small amount of sericitic material occurs in some specimens. The quartzite has a fused appearance and all megascopic indications of a granular texture have been obliterated. Those specimens nearly free of sericite are white in color while those that have a small amount of sericite present have a faint, light-green tint. A schistosity is faintly developed. The quartzite occurs in beds of uniform thickness that are conformable with the other sedimentary beds. Crawford[9] briefly describes the quartzite as a schistose metaquartzite. By metaquartzite he probably means a sandstone with silica cement that has been recrystallized by dynamic metamorphism.

An arkosite found just south of the highest peak on Antelope

[9] *Op. cit.*

Island has a greenish-gray color due to a mixture of quartz and chlorite. Numerous pink grains of altered feldspar stand out against the dark background. An indistinct bedding plane makes about a 35° angle with the schistosity of the specimen. The divergence from parallelism of the schistosity and the bedding is rather exceptional, however, in the Farmington Canyon complex. Such a condition was observed only in three or four places. An arkosite from Bountiful Peak resembles a white quartzite, but close examination reveals the presence of appreciable white feldspar.

The most interesting and significant of the sedimentary rocks studied is a quartz-chlorite conglomerate schist from Bountiful Peak. This rock consists of elongated green chloritic quartzite pebbles in a groundmass of lenticular quartz and chlorite (clinochlore). The pebbles vary in size from $\frac{1}{8}$ inch up to about 1 inch in diameter and are elongated parallel to the plane of foliation. The strongly schistose layers of the groundmass bend around the pebbles, giving the rock as a whole a wavy appearance.

MICROSCOPIC FEATURES

Under the microscope, the metamorphosed sedimentary rocks have a number of features in common. The essential minerals (Table 2), in decreasing order of average abundance, are quartz, chlorite, sericite, and feldspar. Most of the chlorite and sericite is the result of metamorphism and not of weathering. Biotite is scarce and, where present, is usually weathering to chlorite and epidote. The feldspar is generally orthoclase or microcline. However, the arkosite from Bountiful Peak contains oligoclase as the predominant feldspar. Zircon and apatite are the most abundant of the accessory minerals. Sagenitic inclusions of rutile in chlorite are plentiful.

The quartz grains of the rocks of this group are partly outlined by rims of iron oxide and commonly show secondary growths of quartz in optical continuity with the original grains. The grain boundaries are usually sutured, suggesting that the secondary growths are the result of recrystallization due to dynamic metamorphism rather than cementing of the original grains by infiltration of silica. Undulatory extinction, moderate to strong, is universal in the quartz grains. In addition they show incipient cracking with local areas of intense shattering and granulation. These features

are superimposed upon the secondary quartz growths as well as upon the original grains and indicate that straining and shearing movement followed recrystallization. Schistosity is evident but not always well developed and is revealed best by chlorite and mica. Quartz also tends to be elongated parallel to the plane of schistosity. Grain size is variable in the same specimen, ranging up to a maximum diameter of 2 or 3 millimeters.

TABLE 2

MODAL ANALYSES OF THE METAMORPHOSED SEDIMENTARY ROCKS; VOLUME PERCENTAGE ESTIMATED VISUALLY EXCEPT IN NO. 6, WHICH WAS MEASURED WITH A WENTWORTH RECORDING MICROMETER

MINERALS	BOUNTIFUL PEAK						ANTELOPE ISLAND
	Quartz-sericite Schist (No. 5)	Quartz-chlorite Schist (No. 6)	Arkosite (No. 7)	Quartz-chlorite Conglomerate Schist (No. 12)	Chloritic Siltstone (No. 11)	Schistose Quartzite (No. 30)	Arkosite (No. 14)
Quartz	80	68.7	70	50	60	95	40
Chlorite, biotite	5	24.4	5	40	30	5	45
Sericite	15	6.9	.....	10	10	.....	.....
Feldspar	.....	.....	25	.....	.....	.....	15
Total	100	100.0	100	100	100	100	100

The pebble conglomerate, the evidence of an original granular structure, the high-quartz content, and the distinct stratification demonstrate the sedimentary origin of a major part of the rocks of the Farmington Canyon complex. The rocks have been subjected to a medium grade of dynamic metamorphism. The cataclastic effects indicate that the rocks were under a moderate to light load. The straining of the quartz may have been produced during the main period of metamorphism after recrystallization was nearly completed, or by a later deformation.

METAMORPHOSED SILICIC IGNEOUS ROCKS

MEGASCOPIC FEATURES

The silicic igneous rocks are second only to the sedimentary group in abundance. Except for small stocks on Antelope Island, in the

mouth of Ogden Canyon, and in Waterfalls Canyon, the intrusions are represented throughout the area by countless sills and many cross-cutting dikes. Pegmatite is the most conspicuous of the rock types and is either white, gray, or pink, depending upon the color of the microcline present. Around the borders of the pegmatite masses many small veins of related quartz cut the country rock.

The rocks of the stocks are mostly foliated granites and quartz monzonites. They are medium grained with light gray or pink layers of quartz and feldspar alternating with dark biotite. The banding is not so sharp and regular as in the injection gneisses and appears to be a primary feature in some places. Schlieren are well developed in the gray granite in the mouth of Ogden Canyon. Their strike averages due north and their dip 70° east. This corresponds closely with the direction of foliation of the quartz monzonites on Antelope Island. The similarity of the Antelope Island, Waterfalls Canyon, and Ogden Canyon intrusions suggests that their magmas may have had a common origin.

There is no regional granitization of the old sedimentary rocks of the Farmington Canyon complex such as Stark[10] noted in the Sawatch Range in Colorado. Migmatites, if they occur, are confined to the narrow zone in contact with the small stocks that intrude the region.

MICROSCOPIC FEATURES

Quartz and potash feldspar generally comprise 60–80 per cent of the silicic igneous rocks (Table 3). Albite, $Ab_{95-90}An_{5-10}$, is also an important constituent. The usual ferromagnesian mineral is biotite, but a gneissic granite from Ogden Canyon contains abundant green hornblende. The accessory minerals include zircon, apatite, magnetite, orthite, and titanite. Weathering is moderate, albite altering to a white mica, biotite to chlorite, and orthoclase to a clay mineral.

A cataclastic texture has been superimposed upon the original granitoid texture. The original quartz grains have been shattered into smaller pieces and locally granulated at grain boundaries. Undulatory extinction is moderate to strong. Bending and fracturing of the twinning lamellae of albite is common. Apparently some recrystallization of the rocks accompanied the deformation, because

[10] J. T. Stark, "Migmatites of the Sawatch Range, Colorado," *Jour. Geol.*, Vol. XLIII (1935), pp. 1–26.

locally the grain boundaries are somewhat sutured. The cataclastic features give the rocks a very ragged and patchy appearance when viewed under the microscope.

Foliation is usually only weakly developed, although preferred orientation of the quartz, albite, and biotite can be recognized. The fairly uniform regional strike of the foliation is taken as evidence of its metamorphic origin, although primary gneissic structures un-

TABLE 3

MODAL ANALYSES OF THE METAMORPHOSED SILICIC IGNEOUS ROCKS; VOLUME PERCENTAGE MEASURED WITH A WENTWORTH RECORDING MICROMETER EXCEPT IN NO. 13, WHICH WAS ESTIMATED VISUALLY

Minerals	Feldspathic Pegmatite, Antelope Island (No. 13)	Quartz Aplite Gneiss, Bounti-Peak (No. 3)	Gneissic Hornblende Granite, Ogden Canyon (No. 1)	Gneissic Granite, Ogden Canyon (No. 22)	Gneissic Quartz Monzonite, Waterfalls Canyon (No. 27)	Gneissic Quartz Monzonite, Antelope Island (No. 23)
Quartz	20	53.3	24.3	42.3	36.2	38.2
Microcline and orthoclase	80	7.3	41.7	44.7	27.3	28.9
Albite	.....	23.9	16.1	7.9	28.3	18.1
Biotite	.....	14.8	tr.	4.7	4.6	12.1
Hornblende	.....	.....	17.3	.....	.....	.....
Accessories	tr.	0.7	0.6	0.4	3.6	2.7
Total	100	100.0	100.0	100.0	100.0	100.0

doubtedly exist in the area. The cataclastic texture, the somewhat recrystallized grains, and the gneissic banding of the silicic igneous rocks indicate a low to medium grade of dynamic metamorphism. The regional strike of the foliation is the same in both the sedimentary and the igneous rocks and therefore the stocks and associated dikes and sills were intruded into the sediments before or during the main period of metamorphism. Most of the pegmatitic material is somewhat foliated and probably was injected before the close of the metamorphism, but the pegmatites on the east slope of Bountiful Peak are essentially unfoliated and were probably injected shortly afterward.

METAMORPHOSED INJECTION GNEISSES

MEGASCOPIC FEATURES

The injection gneisses are closely related to the silicic igneous rocks. However, because the injection gneisses are part sedimentary

and part igneous in origin, they are treated as a separate group. Throughout most of the area lit-par-lit injections are intercalated with metamorphosed sediments. They are apparently related to the intrusion of the pegmatites and some of the stocks.

The specimens of injection gneiss studied are characterized by sharp gneissic banding. Black bands of biotite $\frac{1}{8}$–$\frac{1}{2}$ inch in width alternate sharply with pink bands containing quartz and feldspar of similar thickness. Individual layers exhibit uniform thickness, sometimes for a distance of several feet. Commonly small seams of the leucocratic layers break across the thin biotite layers. The sharpness and distinctness of the two mineral bands suggest that the biotite bands represent an old sediment, such as shale or slate, which has been split apart by the intruding magmatic material—the quartz and feldspar layers.

MICROSCOPIC FEATURES

Under the microscope the injection gneisses have many features in common with the silicic igneous rocks. The dark bands contain biotite with the basal cleavage parallel to the plane of foliation, garnet, quartz, microcline, and oligoclase, $Ab_{75}An_{25}$. The light bands contain only the three last-mentioned minerals with additional accessory minerals such as zircon, apatite, orthite, and magnetite.

The evidence of metamorphism is much the same as in the silicic igneous rocks. The cataclastic texture occurs locally. A small amount of recrystallization has produced sutured grain boundaries between quartz grains but not between other minerals. The quartz shows undulatory extinction, moderate to strong. The garnet is of particular interest because the injection gneisses are the only type of rock investigated in which it appears. It is red and has an index of refraction corresponding to almandite. The garnet grains average about 1 millimeter in diameter and are elliptical with their long axis parallel to the foliation. Two sets of fractures shatter the garnet grains, one parallel to the plane of foliation, the other making angles between 65° and 80° with the plane of foliation. In the cracks of the garnet are biotite and a little epidote.

The garnet probably represents an early reaction product of the intruding igneous material and the sediment. The fact that the garnet grains are elliptical in shape and have a set of pronounced

fractures nearly perpendicular to the plane of foliation is evidence that the injection of the igneous material took place before or during the main period of metamorphism. The foliation and the recrystallization also support this conclusion. A low to medium grade of dynamic metamorphism is indicated.

METAMORPHOSED MAFIC ROCKS

MEGASCOPIC FEATURES

The rocks which have been grouped under this heading are the least known of the various types that were studied. They are not abundant and where observed are conformable layers between the metamorphosed sediments. They vary in thickness from 1 to 10 feet. No mafic dikes were found by the writers, but other geologists have reported personally their presence. These dark beds could have been formed in any one of three different ways: (1) as a sediment with a high concentration of ferromagnesian material, such as graywacke, (2) as a sill of mafic igneous material, or (3) as mafic lava flows or mafic pyroclastic material.

Two specimens of hornblende-labradorite gneisses were collected from the east slope of Bountiful Peak. They consist of alternate layers of hornblende and labradorite. The foliation is well developed and the bands are about 1 millimeter thick. In appearance they closely resemble a diorite gneiss. Another hornblende gneiss from Antelope Island looks more like a hornblendite. It is black and rather fine grained with the hornblende crystals slightly elongated and parallel.

A specimen of an epidote-chlorite schist from a ridge east of Farmington Flats is one of interest. It is a medium dark-green, fine-grained rock. Foliation is not noticeable in the hand specimen.

In the upper part of Waterfalls Canyon is found a small, but apparently massive, mafic intrusion (?). It is composed of green chloritic rock which has a dioritic appearance.

MICROSCOPIC FEATURES

The two hornblende-labradorite gneisses are very similar in appearance and in mineral composition (Table 4). Quartz and biotite are abundant in one but not in the other. Both rocks have the ferromagnesian minerals oriented in the plane of foliation. The hornblende is euhedral and occurs in crystals up to 3 millimeters

in length. The labradorite, $Ab_{48}An_{52}$, has a mosaic texture while the quartz, when present, has sutured grain boundaries. Recrystallization of these rocks has been complete.

As an aid in interpretation of these rocks, a chemical analysis of the quartz-bearing hornblende-labradorite gneiss was calculated from the modal analysis (Table 5). The analysis corresponds closely to some quartz gabbros as does the mode. The stratified nature of these rocks parallel to the other sedimentary rocks in the Farming-

TABLE 4

MODAL ANALYSES OF METAMORPHOSED MAFIC ROCKS; VOLUME PERCENTAGE MEASURED WITH A WENTWORTH RECORDING MICROMETER EXCEPT IN NOS. 8 AND 29, WHICH WERE ESTIMATED VISUALLY

Minerals	Hornblende-labradorite Gneiss, Bountiful Peak (No. 4)	Hornblende-labradorite Gneiss, Bountiful Peak (No. 8)	Hornblende-Gneiss, Antelope Island (No. 29)	Epidote-chlorite Schist, Farmington Flats (No. 15)
Quartz	21.9	tr.	tr.	1.0
Labradorite	26.0	40	.....	.....
Oligoclase	.....	.....	20	.....
Hornblende	31.5	60	80	.....
Biotite	19.6	tr.	tr.	.....
Epidote and clinozoisite	tr.	tr.	tr.	71.7
Titanite	tr.	.....	.....	5.7
Chlorite	tr.	tr.	tr.	21.1
Accessories	1.0	tr.	tr.	0.5
Total	100.0	100	100	100.0

ton Canyon complex and association of quartz with labradorite are features that suggest the rock to be a metamorphosed graywacke. However, no textural evidence could be recognized that would confirm a sedimentary origin.

The hornblende gneiss from Antelope Island contains chiefly a brown hornblende, a trace of biotite and quartz, and about 20 per cent oligoclase, $Ab_{71}An_{29}$. The rock is medium-fine grained, the hornblende grains averaging about 0.5 millimeters in diameter. They are euhedral and strongly oriented. Apparently the rock has been recrystallized. The evidence here of a sedimentary or an igneous origin is also not decisive.

Possibly the most unusual rock of this group is an epidote-chlorite schist from Farmington Flats. Epidote and clinozoisite, in about equal proportions, constitute 72 per cent of the rock (Table 4) and they occur in euhedral, elongated crystals which have a rather well-defined linear orientation. Interstitial chlorite in felted masses and abundant small grains of titanite constitute the remainder of the rock except for a very small amount of apatite, zircon, orthite, and

TABLE 5

CALCULATED CHEMICAL ANALYSES FROM THE MODAL ANALYSES OF THE HORNBLENDE-LABRADORITE GNEISS, NO. 4, AND THE EPIDOTE-CHLORITE SCHIST, NO. 15, OF TABLE 4—WEIGHT PERCENTAGE

Oxides	Bountiful Peak (Number 4)	Farmington Flats (ridge, east of) (Number 15)
SiO_2	57.7	37.4
Al_2O_3	12.7	24.5
Fe_2O_3	2.8	4.8
FeO	6.8	3.5
MgO	7.4	3.1
CaO	6.0	19.7
Na_2O	2.2	0.1
K_2O	1.9	tr.?
H_2O	1.0	3.7
TiO_2	1.1	2.4
Total	99.6	99.2

strained quartz. The rock has been entirely recrystallized. A chemical analysis was computed from the modal analysis (Table 5). The essential features of the analysis are the high alumina and lime and low silica content. The metamorphism of a graywacke or a calcareous and ferruginous shale could produce a rock such as this. However, certain diabasic or basaltic rocks high in lime and alumina could also have been metamorphosed to produce the epidote-chlorite schist.

Final decision on the origin of the metamorphosed mafic rocks must await further field and laboratory investigation. They are not abundant but their unusual character makes them particularly interesting.

HISTORY OF FARMINGTON CANYON COMPLEX

The sedimentary rocks of the Farmington Canyon complex consist of metaquartzites, quartz schists, arkosites, conglomerate schists, and possibly metamorphosed graywackes. The pebbles in the quartz-chlorite conglomerate schist were definitely derived from a pre-existing siltstone, and the metaquartzites may possibly represent older sediments which have been re-worked. Other rocks such as the arkosites were probably derived directly from some near-by pre-existing igneous rock. As some of the metamorphosed sediments are medium to coarse grained, the site of sedimentation was probably relatively close to the source of the material.

After the deposition of a considerable thickness of sediments, they were thoroughly injected by sills and dikes and intruded by a few small stocks. The igneous material consists of granites, quartz monzonites, and pegmatites. The intrusions probably represent one period of igneous activity that extended over a considerable interval of time. The various degrees of metamorphism of the igneous rocks suggest that they were injected during the prolonged orogeny which resulted in widespread development of foliation and various cataclastic structures.

The recrystallization, cataclastic features, and mineral composition of the Farmington Canyon complex indicate that the metamorphism was of the low- to medium-grade dynamic type. This main period of metamorphism occurred in early or Middle pre-Cambrian time and was much more intense than any deformation since. A deformation at the close of pre-Cambrian time and the Laramide revolution disturbed the pre-Cambrian rocks also, but neither of these appreciably affected the structures left in the rocks by the early or main period of metamorphism, except very locally in fault zones.

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TERTIARY GEOLOGY OF THE SAN ACACIA AREA NEW MEXICO

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ABSTRACT

The San Acacia area includes a part of the Rio Grande depression in central New Mexico and is underlain predominantly by basin deposits of late Tertiary age, the Popotosa and Santa Fe formations. The Popotosa formation, heretofore undescribed, is a tuffaceous fan deposit which was laid down in an enclosed basin during late Miocene (?) time. The Santa Fe formation, of Pliocene and late Miocene (?) age, was deposited in several contemporaneous and contiguous basins, some of which had exterior and others interior drainage. A reconstruction of the paleogeography of the area in Santa Fe time is presented. The Tertiary rocks are downfaulted as a graben between highlands composed predominantly of pre-Tertiary rocks. Minor horsts are found within the Tertiary rocks. There were at least three, and possibly five, episodes of deformation during Tertiary time.

INTRODUCTION

In central and northern New Mexico, the Rio Grande flows through a series of structural basins which are underlain by Tertiary rocks and bordered in most places by highlands composed of pre-Tertiary rocks. These basins are known collectively as the Rio Grande depression.[1] The broad area of plains, which includes Albuquerque and Belen (Fig. 4), extends from the Jemez Mountains southward to San Acacia and is called the Albuquerque-Belen basin. This basin is from 25 to 35 miles wide and about 80 miles long. To the south of San Acacia is the Socorro basin, which includes the Socorro Valley and surrounding plains.

The San Acacia area, as here defined, comprises the southern part of the Albuquerque-Belen basin, the north end of the Socorro basin, and La Jenze subbasin (Snake Ranch Flats) which lies to the west of the Sierra Ladron–Socorro Mountain axis. The area is in the Mexican Highland section of the Basin and Range Province as defined by Fenneman.[2]

[1] Kirk Bryan, "Geology and Ground Water Conditions of the Rio Grande Depression in Colorado and New Mexico," *Regional Planning*, Part VI; *Rio Grande Joint Investigation in the Upper Rio Grande Basin* (Washington: National Resources Committee, 1938), Vol. I, Part II, sec. 1, Fig. 45.

[2] N. M. Fenneman, "Physiographic Divisions of the United States," *Annals Assoc. Amer. Geog.*, Vol. XXVIII (1928), pp. 261–353.

The southern part of the Albuquerque-Belen basin lies between the Sierra Ladron (elevation 9,200 feet) and Los Pinos Mountains (elevation 7,700 feet). The Socorro basin is situated between the Socorro Mountains (elevation 7,200 feet) on the west and low hills to the east. The Rio Grande at San Acacia flows at an elevation of 4,660 feet above sea-level. The gradient of the river is about 4 feet to the mile. The Rio Puerco and the Rio Salado, which enter the Rio Grande from the west, are two of its most important tributaries in New Mexico. La Jenze subbasin is bordered on the west by the Magdalena and Bear Mountains. The southern part of the subbasin, to the northeast of the Magdalena Mountains, is called the Snake Ranch Flats, which lie at an altitude of 6,000 feet, about 1,500 feet above the Rio Grande at Socorro. Streams which flow eastward from the Magdalena Mountains pass through canyons in the Socorro Mountains to join the Rio Grande.

The mountains of the San Acacia area are bordered by broad erosion surfaces or pediments which slope outward in all directions toward the main drainage lines. The Rio Grande flows in an inner trench consisting of bluffs bordering a flood plain which varies from less than 1 mile to more than 3 miles in width. Tributaries flow into this trench in steep-walled gulches or *cañadas* which vary in width from a few hundred feet to more than half a mile. These tributaries are intermittent streams or arroyos which have recently been incised below their former flood plains.

The pioneer work of Lee[3] showed that the Rio Grande flows in a valley which has been carved out of an unconsolidated valley fill. This alluvium was thought to fill partly a wide erosional valley. Recent work[4] shows that the alluvium is deformed, is of late Tertiary age, and fills a basin which is primarily the result of deformation, not erosion.

River gravel, which marks the central axis of the late Tertiary (Santa Fe) basins, has been traced from Buchman southward to Los Lunas (Fig. 4); and, in the Socorro region, *playa* deposits are known to be present. This raises the question as to the relation between the

[3] W. T. Lee, "Water Resources of the Rio Grande Valley in New Mexico," *U.S. Geol. Surv., Water Supply Paper 188* (1907).

[4] Bryan, *op. cit.*

late Tertiary river deposits and the Socorro *playa*. Did the river end in the *playa*, or did it follow a different course? Field studies, during parts of the summers of 1935, 1936, and 1937, show that the late Tertiary river did not flow into the Socorro *playa* but probably passed to the east over the south end of the present Los Pinos Mountains. The study has also revealed the presence of a heretofore undescribed basin deposit (the Popotosa) which represents the transition period between the volcanic activity of Miocene (?) time and the basin deposition of Santa Fe (Pliocene ?) time. The mapping is based on a plane-table survey, supplemented by data from a map of the Belen Division of the Middle Rio Grande Conservancy District and from aerial photographs furnished by the Rio Grande District office of the United States Soil Conservation Service.

PRE-TERTIARY AND EOCENE (?) ROCKS

The pre-Tertiary rocks are of importance in the present investigation because they supplied detrital material to the Tertiary basins. Their distribution is shown on Plates 17 and 26 of Darton's bulletin[5] and on the state geologic map.[6] Figure 6 divides the pre-Santa Fe formations into four lithologic types: pre-Cambrian crystalline rocks, late Paleozoic and Mesozoic sedimentary rocks, Tertiary volcanic rocks, and the Popotosa formation. Granite, schist, and quartzite are the most prominent rock types in the pre-Cambrian complex, which is exposed in the Magdalena, Ladron, Socorro, and Los Pinos Mountains, in La Joyita Hills, and elsewhere. The late Paleozoic and Mesozoic rocks include red and gray sandstone and shale, limestone, and beds of gypsum. To the east of the Rio Grande they are exposed in La Joyita Hills, near the headwaters of the Aqua Torres and the Arroyo Cibola, and at the south end of Los Pinos Mountains. They also appear on the west slope of the Sierra Ladron and over a wide area near Santa Rita.

On the east side of La Joyita Hills Cretaceous sandstone and shale are overlain, apparently conformably, by a thin layer of conglomerate of Eocene (?) age,[7] which contains small pebbles of quartz,

[5] N. H. Darton, "'Red Beds' and Associated Formations in New Mexico," *U.S. Geol. Surv. Bull. 794* (1928)

[6] *Geologic Map of New Mexico*, prepared by N. H. Darton (U.S. Geol. Surv., 1928).

[7] Darton, *op. cit.*, Pl. 17.

quartzite, and granite (Fig. 1). The conglomerate is overlain, apparently conformably, by volcanic rocks of Miocene (?) age. On the west side of the hills about 100 feet of coarse conglomerate rest with a slight angular unconformity on red sandstone, probably of Triassic age. This conglomerate, which is overlain unconformably by Miocene (?) volcanic rocks, contains many large fragments of limestone and sandstone in a reddish sandy matrix.

TERTIARY VOLCANIC ROCKS (MIOCENE ?)

The scattered masses of volcanic rocks which are exposed in the San Acacia area consist predominantly of rhyolitic and andesitic flows and tuffs, together with masses of well-indurated conglomerate. Some basaltic members are present. The beds are highly deformed, with dips varying from 10° to 60°. No precise thickness can be given because the locally complex internal structure of the volcanics has not been mapped. Structure section *B–B′* (Fig. 3) shows 4,300 feet of volcanics to the east of La Joyita Hills. The section contains much repetition of beds by faulting.

The several areas of volcanic rocks are correlated with one another on the basis of lithologic similarity and structural relations. The volcanics are assigned to the Miocene (?) epoch because they unconformably overlie Cretaceous and Eocene (?) sediments and are overlain unconformably by late Tertiary basin deposits which contain fragments of volcanic rock.

In the Socorro mountains Lasky[8] reports that there are about 2,300 feet of volcanic rocks which consist of flows, tuffs, breccias, and conglomerates. Rhyolite and trachyte (?) are the principal flows. A monzonite porphyry intrusive is exposed in one of the prospect pits and indicates a local center of eruption. These volcanics[9] are continuous with those exposed to the east of Silver Creek (Fig. 1; T. 1 N., R. 2 W.) in the San Acacia area. The flows, which immediately underlie the Popotosa formation to the east of Silver Creek, thin and die out toward the south, near the headwaters of San Lorenzo Arroyo, a fact which suggests that the source of these flows was to the north.

[8] S. G. Lasky, "Ore Deposits of Socorro County, New Mexico," *New Mexico School of Mines, State Bur. Min. and Min. Res. Bull. No. 8* (1932), pp. 118–33.

[9] Darton, *op. cit.*, Pl. 17.

The Datil formation,[10] in the Bear Mountains (Fig. 4), consists of at least 2,000 feet of well-indurated tuffs, rhyolite flows, cross-bedded sandstones, and conglomerates and rests unconformably on Cretaceous and older beds. These volcanics came out on a surface of low relief, are very extensive, and were perhaps originally joined to the now scattered outcrops of volcanic rocks in the San Acacia area.

POPOTOSA FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Popotosa formation, heretofore undescribed, represents the transition between the Miocene (?) epoch of volcanic activity and the period of basin deposition which is dominantly of Pliocene (Santa Fe) age. The formation consists of debris eroded from volcanic rocks, plus a slight amount of tuff which was contributed to the basin by relatively small contemporaneous eruptions. The formation is confined to an area on the east side of the Sierra Ladron (Fig. 1).

The Popotosa formation is well exposed in the valley of Silver Creek (Fig. 1; T. 1 N., R. 2 W.). The beds dip in a westerly direction and are cut by numerous faults probably of small displacement. To the east of Silver Creek the formation rests unconformably on volcanic rocks (Fig. 2) of Miocene (?) age (structure section B–B', Fig. 3). Locally the two formations are conformable. The lower part of the Popotosa consists of red tuffaceous sandstone, which is locally cross-bedded. Lenses of gravel contain angular pebbles of volcanic rocks not more than a few inches in diameter. Layers of grayish-brown sandy silt are also present, together with a few lenses of thin-bedded grayish-brown tuff in which are found scattered remains of plants. The upper part of the section (to the west of Silver Creek) contains cross-bedded sandstone and conglomerate and layers of pinkish and grayish tuff. The pebbles are of volcanic rocks, angular, and as much as 6 inches in diameter.

Along the arroyos Popotosa and Yeso (Fig. 1), the Popotosa formation dips westward and consists predominantly of fine-grained sand and red and gray silty clay. There are a few beds of massive

[10] D. E. Winchester, "Geology of the Alamosa Creek Valley, Socorro County, New Mexico," *U.S. Geol. Surv. Bull. 716* (1920), pp. 1–15.

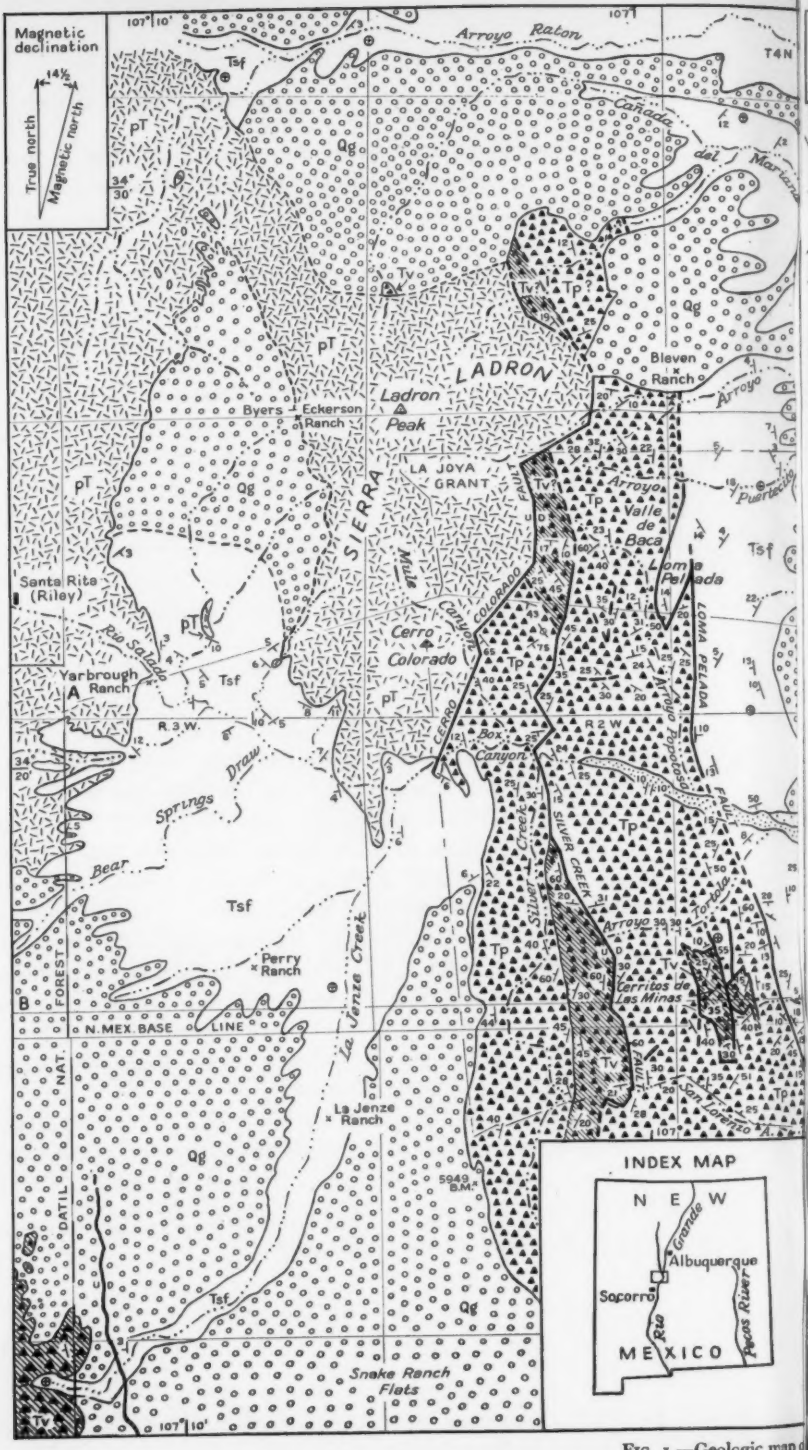
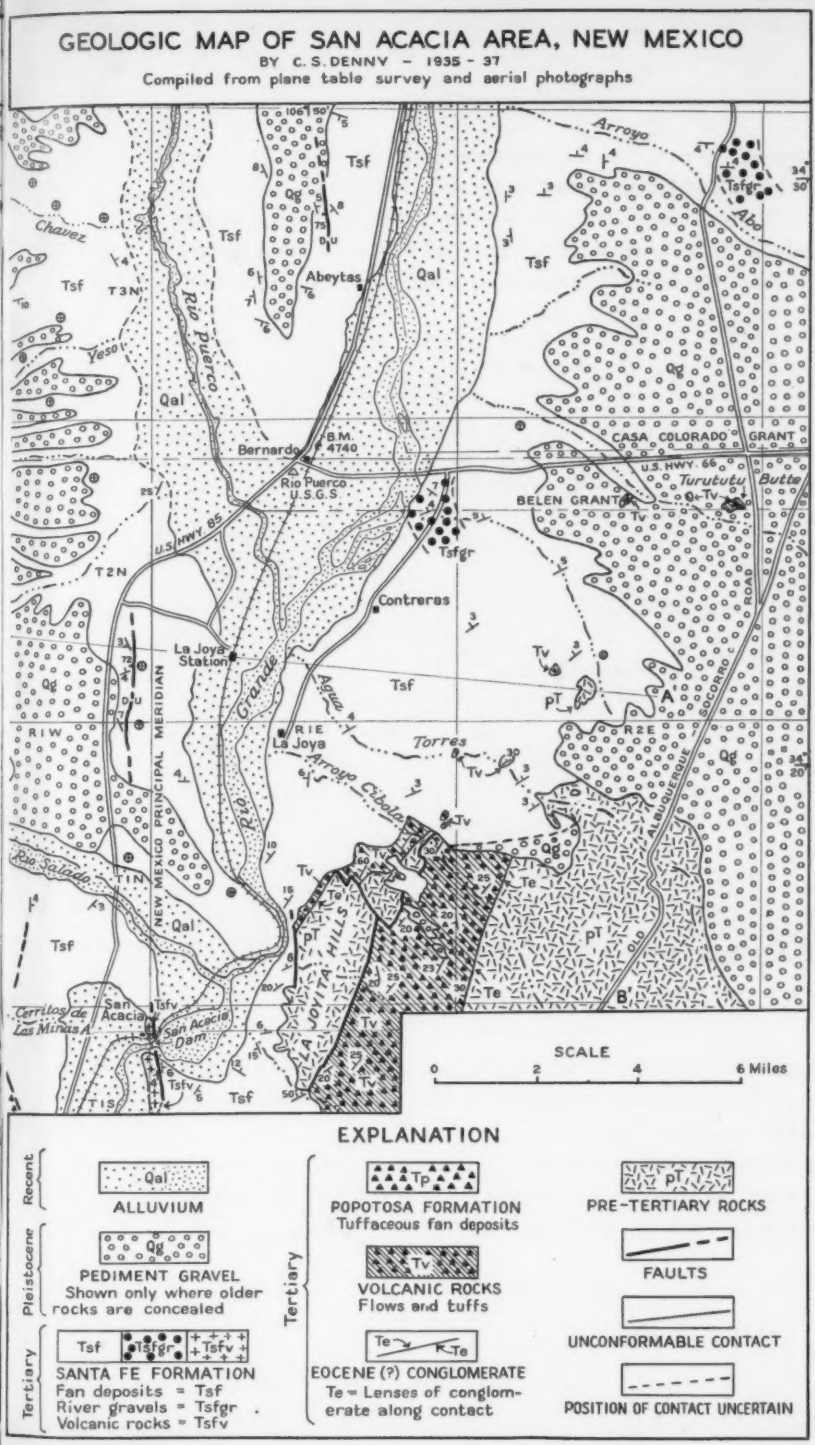


FIG. 1.—Geologic map



San Acacia Area, New Mexico

gypsum which contain an abundance of selenite crystals. The red silty clay includes a few greenish bands and is cut by veins of gypsum. West of these localities the Popotosa consists of bouldery gravel and coarse-grained sand. The pebbles and boulders are angular and are composed of various types of volcanic rocks together with

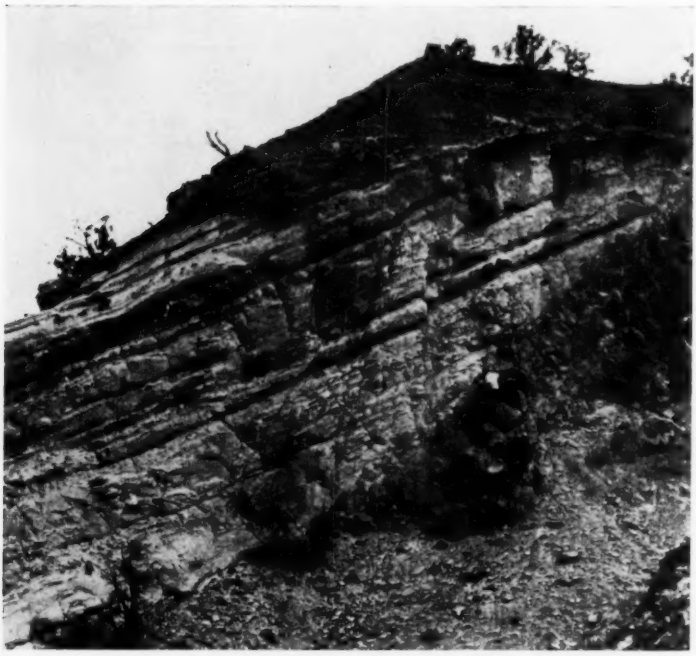


FIG. 2.—Unconformity between Popotosa formation and Tertiary volcanics. Exposure on east side of Silver Creek about 4 miles south of Rio Salado.

granite, schist, quartzite, and sandstone. This coarse-grained section of the Popotosa apparently overlies conformably the finer-grained materials to the east.

Abundant faults make it difficult to estimate the thickness of the Popotosa formation; nevertheless 3,000 feet is probably a minimum figure, with 5,000 feet as a possible maximum.

AGE AND CORRELATION

Inasmuch as the Popotosa formation, to the east of Silver Creek, rests unconformably on volcanic rocks of Miocene (?) age, and, to the west, is overlain unconformably by gravel of the Santa Fe formation which is considered to be dominantly Pliocene in age, the Popotosa formation is assigned, tentatively, to late Miocene time. The Popotosa beds along Silver Creek are correlated with the basin deposits to the east of the Silver Creek fault (Fig. 1), because both series of rocks consist of volcanic debris. In contrast, the surrounding Santa Fe beds contain only a small percentage of such material (Fig. 6). The fact that Santa Fe gravel is downfaulted against these supposed Popotosa rocks along the Loma Pelada fault (Fig. 3) also suggests that the latter are the older.

In the south bank of the Aqua Torres (Fig. 1), on the east side of the Rio Grande, there is an exposure of gray tuffaceous sand, here included in the Santa Fe, which might be a part of the Popotosa formation.

Tuffaceous fan deposits, which lie unconformably beneath the Santa Fe formation, are found elsewhere in the Rio Grande depression. In the Ceja del Rio Puerco, to the northwest of Albuquerque (Fig. 4) there are two exposures of a water-laid, andesitic tuff[11] which are overlain unconformably by the basal member of the Santa Fe formation in that area. The Abiquiu tuff, in the quadrangle of the same name, underlies the Santa Fe formation with only a slight angular unconformity. Locally the two formations are interbedded.[12] On the west side of the Sangre de Cristo Mountains, to the south of Taos, there are outcrops of Picuris tuff[13] which is older than the Santa Fe formation.

ORIGIN

The Popotosa formation is an alluvial deposit which was laid down in an enclosed basin under arid or semiarid climatic conditions.

[11] Kirk Bryan and F. T. McCann, "The Ceja del Rio Puerco: A Border Feature of the Basin and Range Province in New Mexico. I. Stratigraphy and Structure," *Jour. Geol.*, Vol. XLV (1937), pp. 801–28.

[12] H. T. U. Smith, "Tertiary Geology of the Abiquiu Quadrangle, New Mexico," *Jour. Geol.*, Vol. XLVI (1938), pp. 944–52.

[13] E. C. Cabot, "Fault Border of the Sangre de Cristo Mountains North of Santa Fe, New Mexico," *Jour. Geol.*, Vol. XLVI (1938), pp. 88–105.

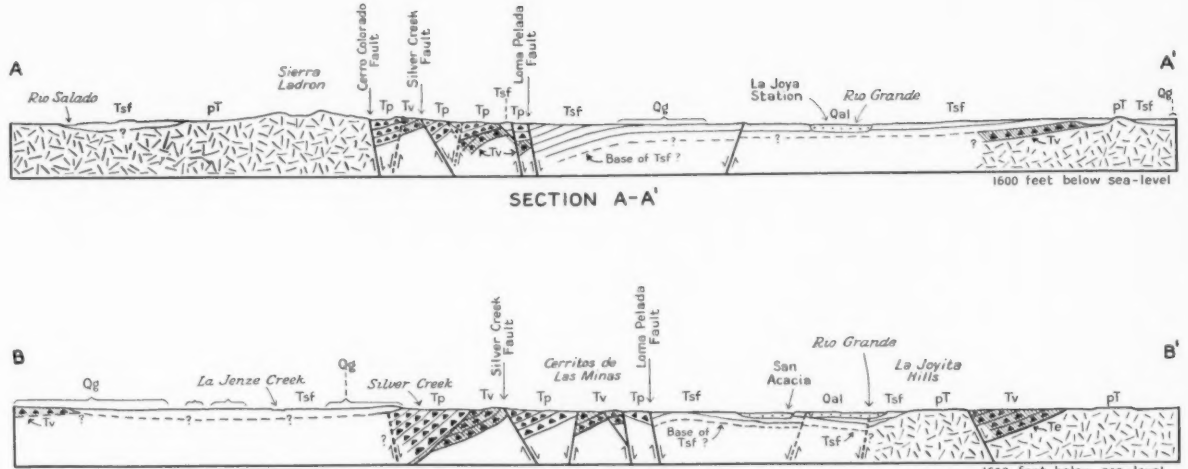


FIG. 3.—Structure sections of San Acacia Area, New Mexico

The conglomerate, sand, and sandy silt are alluvial fan deposits. The silt and silty clay accumulated in a *playa*,[14] in the center of an enclosed basin, as is shown by the fine-grained, rather uniform texture of the material, its regular stratification, and the abundance of gypsum.

The red color suggests evaporation and oxidation in an arid environment, but the color may be the result of the erosion of the Mesozoic "red beds." Green and gray clay implies either an absence of oxidation and, therefore, of deposition in lakes or the reduction of originally red clay by organic matter under lacustrine conditions. These alternations of color indicate that the center of the basin was at times a lake, at others a dry *playa*. Huntington[15] found alternations of red and green clay in the alluvial deposits of the basin of Sistan in arid Turkestan.

The gypsum veins are of secondary origin. Ground water, moving along joint planes, transported and redeposited the salts of the *playa*, which may or may not have originally included gypsum.

The *playa* deposits are confined to a narrow belt which is just west of the Loma Pelada fault (Figs. 1 and 3). In general the beds dip westward (as between arroyos Yeso and Puertecito; T. 2 and 3 N., R. 2 W.), although the geologic map (Fig. 1) shows considerable variety of structure within the formation. The coarser-grained phase of the Popotosa, which is exposed just east of the Silver Creek fault, appears to overlie stratigraphically the *playa* deposits within the Popotosa to the east. Likewise the westward-dipping Popotosa beds along Silver Creek are coarser grained to the west than to the east of the creek (structure section *B–B′*, Fig. 3). Such a change from coarse to fine-grained sediment, which takes place within a distance of about 2 miles (measured parallel to the present surface), is too abrupt to be accounted for by assuming that this change is due to the proximity of highlands to the west during Popotosa time. That is to say it is a more abrupt textural change than would be expected to occur as one passed westward from the Popotosa *playa* toward the

[14] D. G. Thompson, "The Mohave Desert Region, California," *U.S. Geol. Surv., Water Supply Paper 578* (1929), pp. 108 and 125; Bryan, *op. cit.*, p. 207.

[15] E. Huntington, "Basin of Eastern Persia and Sistan," in "Exploration in Turkestan, etc." (Expedition of 1903 under R. Pumpelly), *Carnegie Inst. Wash. Pub. No. 26* (1905), pp. 217–317, Plate V.

bordering highlands of that time. Rather it suggests that the upper part of the formation is coarser grained than the lower, the interpretation assuming an increase in relief between the *playa* and the surrounding highlands during the latter part of Popotosa time.

The alluvial fan deposits of the Popotosa formation were probably derived from the west. The basal layers of the formation, where exposed to the east of Silver Creek, consist of gravel, sand, and silt; whereas, to the northeast of the Cerritos de Las Minas (Fig. 1), there are outcrops of *playa* deposits. If these latter beds are near the base of the Popotosa, it follows that the lower part of the formation is coarser grained westward, suggesting that alluvial fans bordered the *playa* on the west.

The slight angular discordance between the Popotosa formation and the underlying Miocene (?) volcanic rocks and the fine-grained texture of the basal Popotosa suggest that the initial relief of the depositional basin was slight. The underlying volcanics were originally much more extensive than at present, perhaps covering the entire area. At the beginning of Popotosa time a shallow basin was formed in these volcanic rocks. Silt and clay were deposited on the *playa* in the center of this basin, together with various salts. The surrounding fans were composed largely of the debris eroded from volcanic rocks. While these fine-grained alluvial fan and *playa* deposits were being laid down, the surrounding uplands began to rise so that the side streams supplied coarser and coarser detritus. At several different times pumice and ash were contributed to the basin from a near-by center of eruption.

Pebbles of granite, schist, quartzite, and sandstone, which are found in the Popotosa formation, indicate that there were highlands in the Sierra Ladron during Popotosa time. A few miles to the west of Silver Creek there was another highland area which was perhaps the result of pre-Popotosa uplift along the southward continuation of the Cerro Colorado fault (structure section *B*–*B'*, Fig. 3).

SANTA FE FORMATION

INTRODUCTION

The Rio Grande depression, in central and northern New Mexico, is partly filled with deformed alluvial deposits. Fossils found in

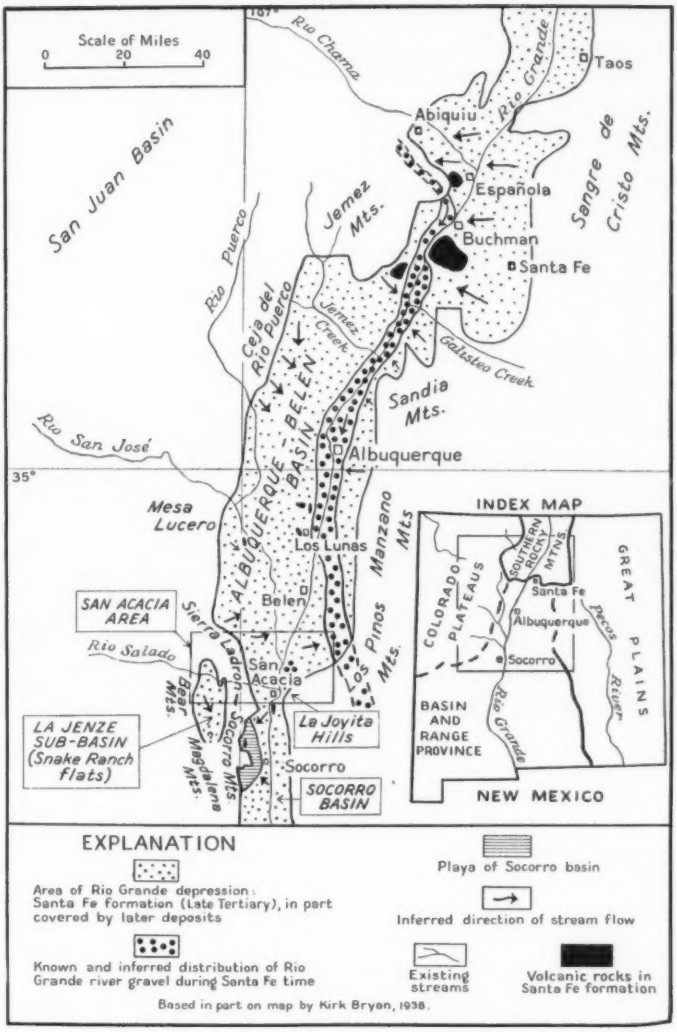


FIG. 4.—Map of Rio Grande depression from Taos to Socorro. Modified from Bryan ("Geology and Ground Water Conditions . . . ." [1938], Fig. 46).

these beds indicate that they are late Tertiary, dominantly Pliocene, in age. Extensive remnants of gravel-capped erosion surfaces and Recent alluvium conceal the late Tertiary rocks over wide areas. These basin deposits are called the Santa Fe formation.[16] In the San Acacia area the Santa Fe formation is widely distributed. It underlies the southern end of the Albuquerque-Belen basin from Abeytas to San Acacia (Figs. 1 and 4) and is extensively exposed in the north end of the Socorro basin and in La Jenze subbasin to the west of the Sierra Ladron–Socorro Mountain axis. The formation consists of alluvial fan and river deposits together with at least one contemporaneous flow of andesitic lava.

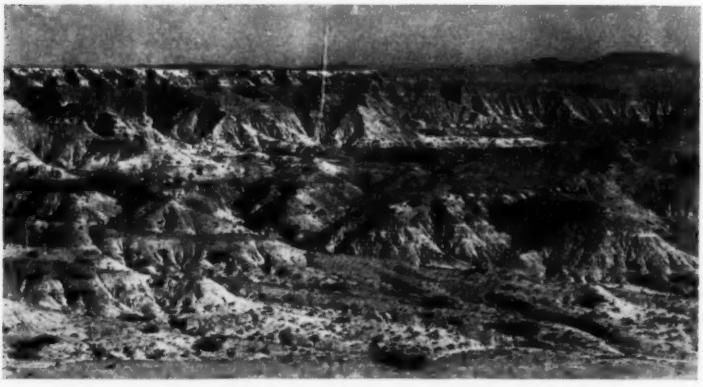


FIG. 5.—Sand, sandy silt, and silty clay of the Santa Fe formation which is exposed in east side of mesa west of Belen.

ALLUVIAL FAN DEPOSITS

The alluvial fan deposits consist predominantly of gravelly or silty sand. However, there are many exposures of coarse-grained gravel which contain angular boulders, the largest of which are 3 feet in diameter, and of lens-shaped masses of cross-bedded gravel and sand. The basal layer of the formation at one exposure is a talus breccia or scree. Locally the pebbles are arranged in an imbricate structure. Most of the gravel is partly cemented by calcium carbonate. Abrupt changes in texture, both within a single bed or from bed to bed, are the rule.

[16] Charles S. Denny, "The Santa Fe Formation," unpublished manuscript (1939).

Sandy silt and silty clay make up only a small fraction of the alluvial fan deposits. Nodular calcareous concretions and clay balls are found in this finer-grained phase.

The lithological variations within the alluvial fan deposits are shown on Figure 6, in which data from sixty-one localities are recorded. On this map the symbols at the various localities represent the

TABLE 1

SECTION OF ROCKS EXPOSED IN EAST SIDE OF MESA TO WEST OF ABEYTAS

	Feet
Quaternary pediment gravel	
Sand (aeolian); contains a basal layer of small rounded and polished pebbles	0–3
Sand; contains much calcium carbonate (caliche)	4
Gravel, gray; contains much sand	6
Unconformity	
Tertiary Sante Fe formation	
Sand, brownish gray, well bedded; contains layers of silt and of silty clay	10
Gravel, gray	3
Sand, grayish white and yellowish brown, fine grained; a few fine-grained, lens-shaped masses of gravel; and narrow bands of red, silty clay	112
Gravel, sandy; contains angular and subangular pebbles of granite, quartzite, schist, quartz, light-brown sandstone, purplish-gray volcanic rocks, and calcareous concretions	22
Sand, grayish white, coarse grained, cross-bedded; contains a few small pebbles and thin bands of reddish-brown, silty clay	44
Thickness of Santa Fe	191

several grain sizes ("gravel," "sand," "fine sand, sandy silt, and silty clay") which are to be found in the Santa Fe at these localities, in approximately the correct proportions. For example, the finer-grained members of the Santa Fe are well exposed in the mesa which separates the Rio Puerco from the Rio Grande (Figs. 1, 5, and 6). In the section (Table 1) from the east side of this mesa to the west of Abeytas (Loc. 1, Fig. 6), there is a predominance of "sand," some "gravel," and a little "fine sand, sandy silt, and silty clay." When

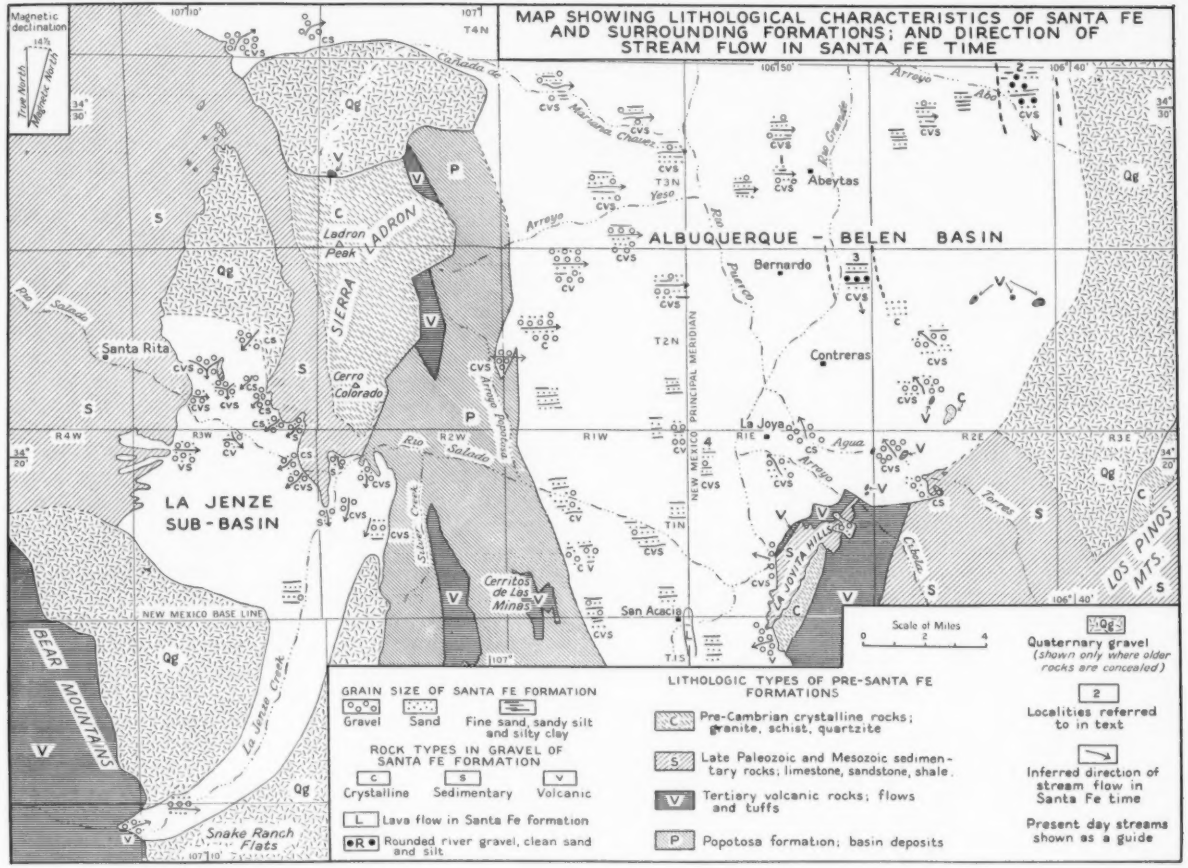


FIG. 6.—Map showing lithological characteristics of Santa Fe and surrounding formations and direction of stream flow in Santa Fe time

viewed from a distance the Abeytas section has a pinkish color. A thin film of reddish silt overlies the outcrop and is washed down from the few narrow bands of silty clay.

RIVER DEPOSITS

In the Santa Fe formation there are two outcrops of gravel, sand, silt, and red and green clay, which are interpreted as the deposits of a large, through-flowing river (Fig. 6). The pebbles are well rounded, the largest being 7 inches in diameter. The majority, however, are not over 3 inches. The sand is well sorted and contains thin bands of pumice and a few pumice fragments as much as 1 inch in diameter. On the north side of Arroyo Abo (Loc. 2, Fig. 6; T. 3 N., R. 2 E.), where an incomplete section (Table 2) was measured, there are exposures of about 50 feet of river-laid beds.

TABLE 2

SECTION OF ROCKS EXPOSED IN NORTH BANK OF ARROYO ABO

	Feet
Santa Fe formation	
Gravel, gray, sandy; contains well-rounded pebbles as much as 6 inches in diameter, the majority not over 3 inches in diameter, of the following rock types: coarse-grained red granite, quartzite, quartz, rhyolite (abundant), basalt and andesite (a few), chert, and one or two limestone	2
Clay, greenish	2
Sand, yellowish gray to buff, fine grained, well sorted	4
Sand, gypsiferous	2
Clay, red, silty	1
Total thickness measured	11

In the bluffs on the east side of the Rio Grande, east of Bernardo, about 40 feet of river gravel, sand, and clay are exposed (Loc. 3, Fig. 6). Here a grayish-white sand contains fragments of equisetum and water-worn pieces of petrified wood.

The fact that the river deposits contain well-rounded pebbles of relatively resistant rocks and much well-sorted sand suggests that these materials were transported by a large river. The fragments of pumice floated down the river because of their low specific gravity. Well-sorted sand, green clay, and the equisetum suggest the presence

of marshes and areas of quiet water on a wide flood plain. Part of the well-sorted sand may be an aeolian deposit. The basin deposits, which surround the river-laid beds, are coarser grained as one approaches the borders of the basin (Fig. 6). This fact suggests that the river-laid beds occupy the axial zone of the basin toward which the surrounding alluvial fans were graded.

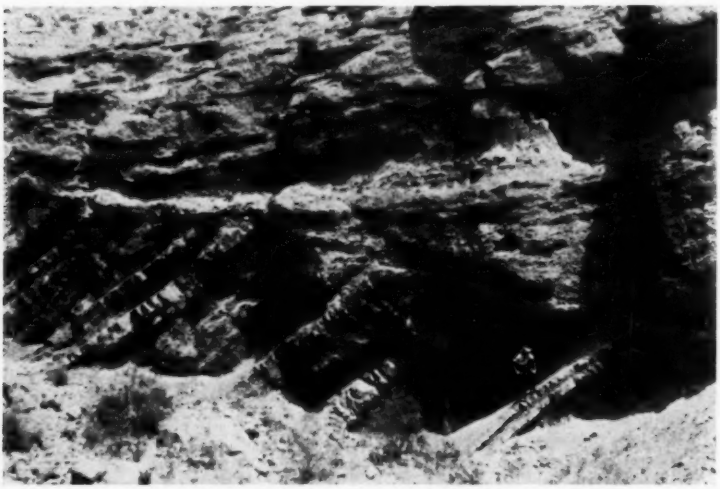


FIG. 7.—Santa Fe formation resting unconformably on pre-Tertiary rocks at south end of La Joyita Hills.

VOLCANIC ROCKS

The Rio Grande at San Acacia flows through a narrow canyon which is cut in a flow of andesitic lava presumably of Santa Fe age. These volcanics dip westward and are overlain by a small mass of fine-grained material which is probably a part of the Santa Fe formation (Fig. 1). Volcanic rocks in the Santa Fe formation are found at several localities outside of the San Acacia area (Fig. 4).

STRUCTURAL RELATIONS

Along the eastern border of the area, the Santa Fe formation rests unconformably on the older rocks (Figs. 1 and 7). To the west of La Joyita Hills this unconformity is broken by a fault. To the east of the

Sierra Ladron the Santa Fe is downfaulted against the Popotosa formation along the Loma Pelada fault. To the northwest of the Sierra Ladron, along the Arroyo Raton, the Santa Fe beds rest unconformably on pre-Tertiary rocks.

At the western end of the Box Canyon of the Rio Salado (Fig. 1) the unconformity at the base of the Santa Fe formation slopes down to the west at the rate of about 100 feet to the mile (Fig. 8). To the

FIG. 8.—Santa Fe formation unconformable on Popotosa beds at west end of Box Canyon of Rio Salado.

east of Santa Rita, both to the north and to the south of the Rio Salado, the unconformity descends to the southeast at about 200–250 feet per mile. The pre-Tertiary rocks appear at the surface within the area of Santa Fe beds to the north of the Rio Salado, where the unconformity has a local relief of at least 40 feet (Fig. 9).

Near the bounding faults the dips of the Santa Fe strata may reach 50° but are in general not over 5°–10°. There are several recognizable faults within the formation.

THICKNESS

The total thickness of the Santa Fe formation cannot be given because of a lack of continuous sections and the abundance of faults.

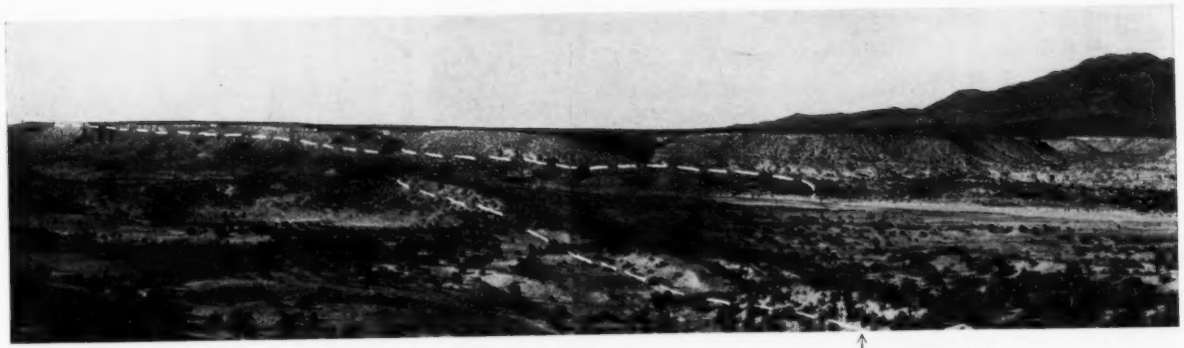


FIG. 9.—View looking northward across Rio Salado to Ladron Peak. Mesa (in middle distance) is underlain by Santa Fe formation which rests unconformably on pre-Tertiary rocks.

Along the Arroyo Puertecito east of the Loma Pelada fault (Fig. 1) there are more or less continuous exposures of about a 2,000-foot thickness of westward-dipping strata. This figure probably represents a minimum value for the formation as a whole. Structure section *A–A′* (Fig. 3) assumes a thickness of about 6,000 feet of Santa Fe beds just east of the Loma Pelada fault. It is probable that the beds are repeated along faults not mapped and that the true maximum thickness is considerably less than that figure.

AGE AND CORRELATION

The Santa Fe formation in the San Acacia area is correlated with the basin deposits in adjacent parts of the Rio Grande depression on the basis of the following evidence: (1) fossil content, (2) continuity of the deposits, and (3) the fact that the materials "conform in their arrangement to a geographic pattern consistent with the laws of deposition in basins."[17]

Fossils were found at two localities in the San Acacia area. A small collection of bone fragments was gathered from beds of sand and pebbly gravel which are exposed in bluffs on the west side of the Rio Grande, about 2 miles southwest of La Joya (Loc. 4, Fig. 6). From this collection Dr. George White, of the Harvard Museum of Comparative Zoölogy, identified the following: *Stegomastodon mirificus Leidy*, which, according to Osborn, is of Upper Middle-Pliocene to Upper Pliocene in age; and a horse's tooth, of the genus *Equus*, probably of Upper Pliocene age. On the east side of the Rio Grande, about 2 miles north of Contreras, plant remains were found in beds of sandy silt and clay which are interbedded with the Santa Fe river deposits (Loc. 3, Fig. 6). Dr. W. C. Darrah, of Harvard University, examined the specimens and reports that they contain a legume, a member of the Black Oak group, and equisetum (rush) of almost modern aspect. This assemblage cannot be precisely dated, but it is certainly post-Miocene in age.

These fossils suggest that the Santa Fe formation in this area is Middle to Upper Pliocene in age. This date is slightly younger than that which is assigned to the Santa Fe fauna in the type locality to

[17] Bryan, *op. cit.*, p. 205.

the north of Santa Fe, where the beds are dated as "late Tertiary," probably late Miocene or Lower Pliocene and possibly younger.[18]

The continuity of the deformed basin deposits can be traced from the type locality southward to the San Acacia area. Bryan and McCann[19] trace the continuity from Santa Fe westward to the Ceja del Rio Puerco (Fig. 4). Fossils found in the basin deposits exposed in the Ceja included "two species of *Merycodus* (which) are characteristic of the known Santa Fe fauna," and several other species compatible with them. Undisturbed sand and gravel, which are exposed in the vicinity of Albuquerque, were described by Bryan[20] in 1909 under the name of "Rio Grande beds." These beds are undoubtedly a part of the deformed valley fill and should be referred to the Santa Fe formation.

Near Los Lunas (Fig. 4) deformed fan deposits are associated with basaltic lava flows.[21] From Los Lunas southward the slightly deformed fan deposits are almost continuously exposed in the east slope of the mesa which separates the Rio Puerco from the Rio Grande.

In the Socorro quadrangle, which adjoins the San Acacia area on the south, there are outcrops of deformed basin deposits which are continuous with those in the latter area. Fossils found by Needham[22] at two localities are probably of Upper Pliocene age.

ORIGIN

Formation of depositional basins.—The Santa Fe formation was deposited in basins the origin of which is not definitely known. The Sierra Ladron and La Joyita Hills were highlands during Santa Fe time (see section on "Paleogeography," p. 96). It is probable that these areas were elevated or the neighboring basins depressed by normal faulting which took place previous to or early in Santa Fe time (see section on "Post-Popotosa—pre-Santa Fe deformation," p. 102).

Near the Loma Pelada (Fig. 1; T. 2 N., R. 1 and 2 W.) there are

[18] Denny, *op. cit.* [19] *Op. cit.*

[20] "Geology of the Vicinity of Albuquerque," *Univ. New Mexico Bull., Geol. Ser.*, Vol. III (1909), pp. 1–24.

[21] Bryan, "Geology and Ground Water Conditions . . . . ," *op. cit.*, p. 209.

[22] C. E. Needham, "Vertebrate Remains from Cenozoic Rocks," *Science*, Vol. LXXXIV (new ser.; 1936), p. 537.

from 1,000 to 2,000 feet of coarse gravel which is composed predominantly of pebbles of crystalline rocks. During the deposition of this gravel the pre-Cambrian crystalline rocks of the Sierra Ladron were uplifted relative to the basin, probably at several successive intervals.[23] There is the question of whether or not these movements took place along any of the faults shown on the geologic map (Fig. 1). There has been no movement along the Cerro Colorado fault since the deposition of the Santa Fe gravel in the valley of La Jenze Creek (La Jenze subbasin), because the fault passes under this gravel at the western end of the Box Canyon of the Rio Salado. The Loma Pelada fault separates the Santa Fe from the Popotosa formation. There is no evidence to indicate that there was movement along this fault during Santa Fe time.

The Silver Creek fault (Fig. 1) is the northward continuation of the fault (or fault zone) which bounds the Socorro Mountains on the east (Fig. 4). They were elevated in post–Santa Fe time. It is possible that the Sierra Ladron was uplifted and tilted westward during Santa Fe time by successive movements along that part of the Silver Creek fault which lies to the north of the Rio Salado. Such movements would form La Jenze subbasin, which lies between the Sierra Ladron and Santa Rita and extends southward to include the valley of La Jenze Creek and the Snake Ranch Flats. Whatever the origin of the subbasin, it was widened by erosion and filled with sediment during Santa Fe time. It may be that other faults, within the subbasin but at present concealed, are of importance in its formation. If the deposits of La Jenze subbasin are late Santa Fe in age, the uplift of the Sierra Ladron, during early Santa Fe time, might have taken place along the Cerro Colorado fault. Following the last movement on this fault the La Jenze subbasin was widened considerably by erosion and then filled with late Santa Fe beds.

Northwest of the Sierra Ladron and also on the east side of the Rio Grande the Santa Fe formation rests unconformably on the older rocks. It is probable that at these localities the Santa Fe basin, originally depressed along faults, was widened because of the retreat of the slopes of the bordering highlands. The Santa Fe beds com-

[23] C. R. Longwell, "Sedimentation in Relation to Faulting," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 433–42.

pletely filled the basin and then overlapped this erosion surface (Lawson's "sub-alluvial bench") to produce the unconformity which is now visible.[24]

Paleogeography.—From a study of the lithological characteristics of the Santa Fe and surrounding formations, as presented in Figure 6, it is possible to reconstruct something of the paleogeography of Santa Fe time. The arrows in Figure 6 indicate the direction of flow of the streams which laid down these alluvial fan and river deposits. The direction of an arrow at any given locality is based on a study of the grain size and rock composition of this outcrop and of the surrounding outcrops of the Santa Fe, and of the neighboring areas of pre–Santa Fe rocks which are the possible sources of detrital material. The paleogeographic map (Fig. 10), is based on the data presented in Figure 6 and on additional data gathered by Bryan[25] in the surrounding region.

The Sierra Ladron and La Joyita Hills were highlands during Santa Fe time and were connected by an alluvial divide (Fig. 10). The center of the Socorro basin was a *playa*, the deposits of which are now exposed just east of the Socorro Mountains (cf. Figs. 4 and 10). La Jenze subbasin is shown as a part of the Socorro basin. River deposits occupy parts of the Albuquerque-Belen basin somewhat to the east of its central axis. In post–Santa Fe time, the Socorro Mountains have risen athwart the *playa* of the Socorro basin, and Los Pinos Mountains have been elevated across the course of the river which flowed through the Albuquerque-Belen basin (cf. Figs. 4 and 10).

Rio Grande of Santa Fe time.—River deposits are found at various localities throughout the Rio Grande depression from Buchman, Santa Fe County, southward to the San Acacia area (Fig. 4). The most northerly outcrops are found at the north end of the White Rock Canyon of the Rio Grande, near Buchman,[26] where the stones

[24] A. C. Lawson, "The Epigene Profiles of the Desert," *Univ. Calif., Dept. Geol. Sci. Bull.*, Vol. IX (1915), pp. 23–48.

[25] "Pediments Developed in Basins with Through Drainage as Illustrated by the Socorro Area, New Mexico" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 128–29, and "Ground Water Reconnaissance in Socorro County, New Mexico," *New Mexico State Engineer, VII Biennial Rept.* (1926), pp. 81–86.

[26] Bryan, "Geology and Ground Water Conditions . . . ," *op. cit.*, p. 207; Denny, *op. cit.*

in the river gravel are from 6 inches to 1 foot in diameter. The river gravel can be traced more or less continuously to Albuquerque.

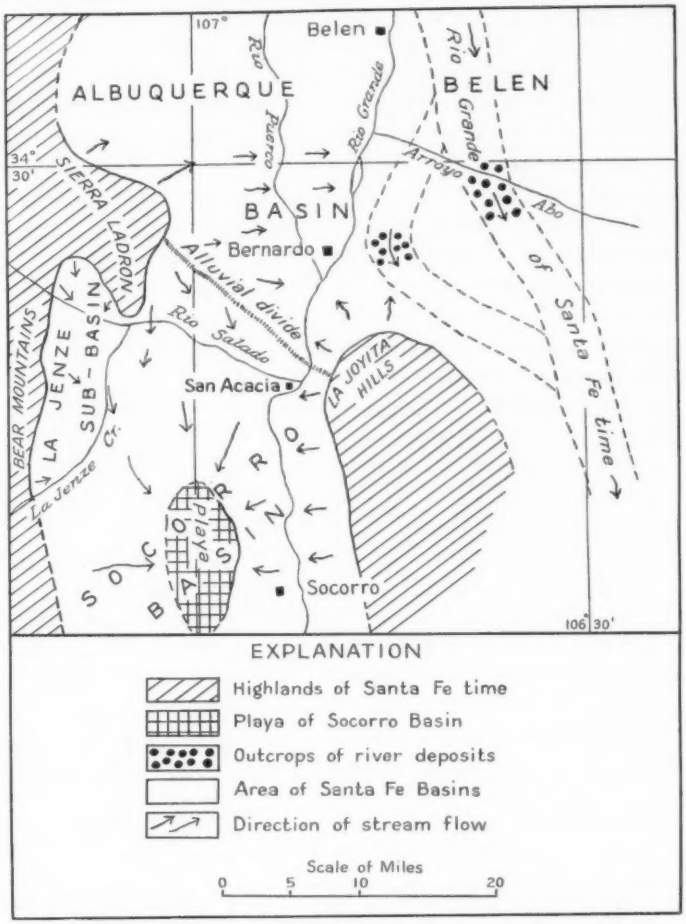


FIG. 10.—Paleogeographic map of San Acacia and surrounding areas during Santa Fe time.

To the south, the only known outcrops are near Los Lunas and in the San Acacia area. There is a gradual decrease in grain size as one goes south from Buchman. In the exposures along the Arroyo Abo (San

Acacia area) most of the water-worn pebbles in the river deposits are less than 3 inches in diameter.

The Santa Fe formation is in general progressively coarser-grained southward and westward from the outcrops of river gravel toward the borders of the Albuquerque-Belen basin (Fig. 6). Therefore the paleographic map (Fig. 10) shows streams which, during Santa Fe time, flowed eastward from the ancestral Sierra Ladron and northward from the ancestral La Joyita Hills toward the Rio Grande of Santa Fe time. Inasmuch as the beds are deformed, very little is known regarding the precise stratigraphic position of the outcrops shown on Figure 6. An objection to any paleographic interpretation is the possibility that it is based on scattered outcrops which are not necessarily related to one another. However the outcrops do "conform in their arrangement to a geographic pattern which is consistent with the laws of deposition in basins."[27]

To the east of the Sierra Ladron, the Santa Fe formation (structure section A–A', Fig. 3) is in the form of a wedge which thins eastward and is cut off at the west along the Loma Pelada fault. According to this interpretation the Santa Fe river deposits, east of the present Rio Grande, belong to the lower part of the formation, whereas the coarse-grained fan deposits, which are exposed to the west near the Loma Pelada fault, are in the upper part of the formation. Inasmuch as the Sierra Ladron was uplifted along the Cerro Colorado fault in post-Popotosa—pre-Santa Fe time and possibly also in early Santa Fe time (see section on "Cenozoic Periods of Deformation," p. 101), there probably were, in early Santa Fe time, alluvial fans which stretched eastward from the ancestral Sierra Ladron toward the position of the present outcrops of Santa Fe river deposits.

In the southern part of the Albuquerque-Belen basin (Fig. 4) the apparent scarcity of outcrops of river deposits may be the result of two factors. In the first place, the total number of exposures of the Santa Fe formation is limited; and, second, the deposition of river gravel by an alluviating stream is dependent upon the size of the basin and the rate of rise of base-level, as well as on the regime of the river. If the basin of deposition is wide and if base-level rises rapidly, much alluvial fan material might be mixed with the river deposits to

[27] Bryan, "Geology and Ground Water Conditions . . . . ," *op. cit.*, p. 205.

make the recognition of the latter as distinct from fan deposits the more difficult. The river gravel would probably be in the form of lenses, which would be scattered throughout the fan deposits over a wide area, rendering it less likely that the river-laid beds would be exposed in the scattered outcrops of the present day. The abundance of Santa Fe river gravel, which is exposed along the Rio Grande from Buchman to the mouth of Jemez Creek (Fig. 4), may be explained by assuming that the river was confined to a narrow channel by the three masses of intra–Santa Fe volcanic rocks which are exposed in that region.

The demarcation of the Santa Fe river gravel on Figure 4 implies a more definite knowledge of the course of the river than is perhaps justified by the meager data available. Nevertheless, the map illustrates clearly the interpretation presented here. The *playa* deposits in the Socorro basin indicate that the Rio Grande of Santa Fe time did not flow into that basin but probably turned to the east of the basin, over the present Los Pinos Mountains.

CLIMATE OF SANTA FE TIME

The abundance of gravel and the rapid horizontal and vertical textural changes in the Santa Fe formation suggest considerable rainfall of the cloudburst type. A perennial river, apparently larger than the present Rio Grande,[28] with a drainage basin certainly no larger than that of the present day, would indicate, for the region as a whole, either a greater rainfall in Santa Fe time than at present or a smaller loss thereof by evaporation, transpiration, and infiltration. The plant remains, found near Contreras, are not diagnostic as to the climate. However, the presence of mastodon and horse necessitates a considerable amount of vegetation. The climate was probably seasonal in character, with considerable rain at certain times of year, to be followed by drought at other seasons.

GEOLOGIC STRUCTURE

GENERAL CHARACTER OF DEFORMATION

The dominant structures of the San Acacia area are tilted horsts and grabens which are bounded by normal faults. The average trend

[28] Pebbles found at depths of about 30–60 feet in the flood-plain deposits of the present Rio Grande are smaller than those which are found in adjacent outcrops of Santa Fe river gravel.

of such features is north–south, parallel to that of the Rio Grande depression. Folding is of only minor importance in the development of the regional structure. The normal faults are divisible into two classes: (1) those which separate, or are entirely within, the two formations that are basin deposits, the Popotosa and the Santa Fe; and (2) those which are between either of these formations and the pre-Tertiary rocks.

In some places the faults that lie within the basin deposits have only one plane of movement. Elsewhere a fault zone is present. The dips of the individual fault planes vary from 50° to 80°. Locally the beds on the downthrow side are dragged up along the fault. Conglomerate and sand dikes are found along some of the fault planes but are not continuous along the strike, nor are they more than 3 feet in thickness.[29] One of the best illustrations of this type of fault is found just east of U.S. Highway No. 85, between Rio Puerco and Rio Salado (Fig. 1).

Faults which separate basin deposits from pre-Tertiary rocks are found on the east side of the Sierra Ladron and on the west side of La Joyita Hills (Fig. 1). The Cerro Colorado fault (T. 2 N., R. 2 W.) is not well exposed, but it appears to be a fault zone, which is as much as 1,000 feet across in some places. On the western edge of the zone, the pre-Tertiary crystalline rocks of the Sierra Ladron are intensely brecciated and show an abundance of slicken-sided surfaces. To the east of the zone Popotosa gravel dips steeply westward. The fault zone contains slivers of the various intervening formations which have been brought up along it. The rocks show evidences of hydrothermal alteration, such as the presence of copper carbonates. Prospect pits are abundant.[30]

Very broad, open folds are shown within some of the fault blocks in the accompanying structure sections (Fig. 3). These folds were probably caused either by compressional forces developed by the downdropping of wedge-shaped grabens which narrow with depth or by the differential settling of the blocks. Small folds are visible in certain exposures, as within the Popotosa formation on the south bank of the Rio Salado.

[29] Bryan and McCann, *op. cit.;* Denny, *op. cit.*

[30] Lasky, *op. cit.*, pp. 89–90.

HORST AND GRABEN STRUCTURE

Near the western edge of the southern end of the Albuquerque-Belen basin, which extends from Abeytas to San Acacia (Fig. 1), the late Tertiary basin deposits are cut by a complex fault system which gives rise to several minor horsts and grabens, the most conspicuous of which is the Cerritos de Las Minas (T. 1 N., R. 1 W.; and structure section *B–B′*, Fig. 3).

The Cerritos are composed of westward-dipping flows and tuffs which are bounded on all sides by faults. The faults are assumed to dip outward in all directions, although the actual contact has been observed at only a few localities. A dip as low as 35° was recorded, but in general the faults are thought to have steep dips, from 70° to 80°. There is a tendency for the surrounding basin deposits to dip away from the center of the hills.

La Joyita Hills, east of San Acacia, are composed of pre-Tertiary rocks. To the east Tertiary volcanic rocks are downfaulted against the pre-Tertiary rocks of the hills (structure section *B–B′*, Fig. 2). To the west these rocks are overlain unconformably by the Tertiary volcanics and the Santa Fe formation (Fig. 1). Locally the unconformity is broken by faults.

The Sierra Ladron is a tilted fault-block mountain. Its eastern face is bounded by a normal (?) fault (Cerro Colorado) which brings the Tertiary volcanics and the Popotosa sediments into contact with the pre-Cambrian crystalline rocks, which form the crest of the range. Westward-dipping Mississippian (?) and Pennsylvanian limestones (not differentiated on Fig. 1) lap up on the mountain from the west,[31] and are overlain unconformably by the Santa Fe formation. No faults have been found on the western side of the range.

CENOZOIC PERIODS OF DEFORMATION

Deformation has taken place at various times throughout the Cenozoic era. Movement has probably occurred along many of the faults at several different intervals of time.

Post-Eocene (?)–pre-Miocene (?) deformation.—The major topographic features of the region originated during the post-Eocene (?)–pre-Miocene (?) interval. The volcanic rocks of La Joyita Hills rest

[31] Darton, *op. cit.*, Pl. 26.

on Eocene (?) conglomerate with but slight angular unconformity. In the Bear Mountains, the unconformity at the base of the Datil formation[32] represents some deformation and considerable erosion which took place in post-Cretaceous–pre-Miocene (?) time.

Popotosa (late Miocene ?) deformation.—After the great epoch of volcanic activity, (Miocene ?) deformation must have taken place to form the basin in which the Popotosa formation was later deposited. To the west of Silver Creek, during Popotosa time, there may have been highlands elevated by movement along a southward continuation of the Cerro Colorado fault.

Post-Popotosa—pre-Santa Fe deformation.—The presence of several thousand feet of Santa Fe beds requires the formation of a depositional basin and the elevation of the bordering highlands at the beginning of Santa Fe time. The Cerro Colorado fault separates the Popotosa formation from the pre-Tertiary rocks of the Sierra Ladron. At the west end of the Box Canyon of the Rio Salado, the deformed Popotosa and the pre-Tertiary rocks, including limestone, are beveled by an erosion surface on which the Santa Fe formation rests (Fig. 8). The stratigraphic throw along the Cerro Colorado fault (structure section *A–A′*, Fig. 3) is probably of the order of several thousand feet. A more definite figure cannot be given because of a lack of precise data as to the thickness of the formations involved. Some movement may have taken place both before and during Popotosa time.

Structure section *B–B′* (Fig. 3) shows a concealed post-Popotosa—pre–Santa Fe fault on the west side of Silver Creek, along which the stratigraphic throw, according to the structure section, is 6,000 feet. It is probable that the Popotosa beds in the valley of Silver Creek are repeated by faulting (along faults not shown in structure section *B–B′*) and that the stratigraphic throw along the fault is considerably less. This hypothetical fault is probably a continuation of, or closely related in age to, the Cerro Colorado fault.

On the east side of La Joyita Hills, the Tertiary volcanics are in contact with the pre-Tertiary rocks along a normal fault (structure section *B–B′*, Fig. 3). The fault is of pre–Santa Fe age because it

[32] Winchester, *op. cit.*

passes under that formation to the north and south of the hills. This fault is offset by another fault which trends nearly at right angles to it and crosses the hills from southeast to northwest where it apparently passes under the Santa Fe formation. The movement along these faults occurred during the post-Volcanic—pre-Santa Fe interval, but their relation to Popotosa time is unknown. The wedge of Tertiary volcanics to the east of the hills has an apparent thickness of about 4,300 feet in structure section *B–B′*. The beds are probably repeated by faults not shown in the structure section, and the true thickness is probably not more than 3,000 feet, which is, therefore, the minimum stratigraphic throw along the fault on the east side of the hills. The Tertiary volcanics, to the east of La Joyita Hills, rest unconformably on Upper Cretaceous rocks; whereas, on the west side, the volcanics rest on Permian strata (Chupadera and Abo).[33] The maximum thickness of beds from the top of the Upper Cretaceous to the base of the Chupadera (Permian) is about 2,300 feet. Therefore, the maximum possible stratigraphic throw along this fault is about 5,300 feet.

Santa Fe (late Miocene? and Pliocene) deformation.—The abundance of gravel in the Santa Fe beds which are exposed near the western edge of the Albuquerque-Belen basin, just east of the Sierra Ladron, presupposes successive uplifts of the Sierra Ladron during Santa Fe time. This movement may have taken place along the Silver Creek fault or possibly along the Cerro Colorado fault (see previous discussion under "Formation of Depositional Basins," p. 94).

Post–Santa Fe (early Quaternary?) deformation.—Structure section *A–A′* (Fig. 3) shows about 5,000 feet of Santa Fe beds east of the Loma Pelada fault. This figure is a possible value for the stratigraphic throw along the fault. However, repetition of beds by faulting and the possibility that a part of the Popotosa formation was removed by erosion from the vicinity of the fault in pre–Santa Fe time make any estimate of doubtful validity.

Northeast of the Sierra Ladron the Loma Pelada fault (Fig. 1) passes under Quaternary pediment gravel and is lost. It is possible

[33] These pre-Tertiary rocks are not differentiated on Fig. 1; see Darton, *op. cit.*, Pl. 17 and Fig. 9.

that it extends to the northwest beneath this gravel and joins the fault which forms the western border of the Rio Grande depression to the south of the Mesa Lucero (for location, see Fig. 4; fault is shown on geologic map of New Mexico in Darton, *op. cit.*).

On the west side of La Joyita Hills a post–Santa Fe fault extends for about $1\frac{1}{2}$ miles. The amount of displacement along this fault is probably not more than a few hundred feet. Between La Joyita Hills and Los Lunas (Fig. 4) there is probably a concealed fault[34] which separates the Santa Fe from the older rocks of the Manzano and Los Pinos Mountains to the east.

Late Pleistocene or Recent deformation.—The Magdalena and Bear Mountains (Fig. 4) have been uplifted in late Pleistocene or Recent times along a fault whose scarp parallels the east face of the mountains.[35] The north end of this fault is shown on Figure 1 to the west of the Snake Ranch flats. This feature and others of Quaternary date will be described in later papers.

Conclusions.—In the southern part of the Albuquerque-Belen basin the oldest faults are nearest the borders of the basin. Progressively younger faults are situated nearer and nearer the axis of the basin. The Cerro Colorado fault which is farthest from the axis of the basin is of pre–Santa Fe age. The Silver Creek fault, to the east, is probably an intra–Santa Fe fault, and the Loma Pelada fault is post–Santa Fe in age. On the east side of the Rio Grande the relations are not so striking; nevertheless the fault to the east of La Joyita Hills is pre–Santa Fe, whereas that to the west is a post–Santa Fe fault.

RÉSUMÉ OF TERTIARY HISTORY

In the San Acacia area, during late Cretaceous or early Eocene (?) time, highlands were formed which yielded coarse detritus that was later deposited to form a conglomerate of Eocene (?) age. What additional events occurred in Eocene and Oligocene times are unknown. It is presumed that during this interval deformation took place and was followed by a long interval of erosion.

During Miocene (?) time several thousand feet of andesitic and

[34] Bryan, "Geology and Ground Water Conditions . . . . ," *op. cit.*, p. 213.

[35] Bryan, "Ground-Water Reconnaissance . . . . ," *op. cit.*, p. 85.

rhyolitic lava flows and tuffs were extruded from centers of activity in the Socorro Mountains, in the Bear Mountains, and elsewhere. Locally the volcanics were eroded, and the fragmental material was redeposited as gravel and water-laid tuff.

Toward the close of Miocene (?) time volcanism subsided, and the volcanic rocks were considerably deformed and eroded. Later deformation produced the enclosed basin in which from 3,000 to 5,000 feet of Popotosa beds were laid down. At the center of the basin there was a *playa* wherein fine-grained alluvium and salts were deposited. The climate of Popotosa time was probably semiarid. Local centers of eruption contributed volcanic ash to the accumulating sediments at several different intervals. As time went on the highlands rose relative to the basin, and coarser material was deposited therein.

In late Miocene (?), or possibly in early Pliocene time, deposition ceased, and the Popotosa beds were considerably deformed and eroded. Continued deformation produced new structural basins in which the Santa Fe formation began to accumulate. In the San Acacia area there were parts of two contiguous basins during Santa Fe time. One, the Albuquerque-Belen basin, was situated to the north of San Acacia; the other, the Socorro basin, lay to the south. The two basins were separated by an alluvial divide which extended from the Sierra Ladron to La Joyita Hills. Alluvial fans stretched outward in all directions from the bordering highlands to the central portion of each basin. The axial portion of the Albuquerque-Belen basin was marked by a perennial river which followed a course that was more or less parallel to the present Rio Grande only as far south as Los Lunas, where the Santa Fe river turned southeastward and flowed across the area now occupied by the southern end of Los Pinos Mountains. A *playa* or *playa* lake marked the central portion of the Socorro basin. Deposition continued throughout Pliocene time until several thousand feet of alluvial material had accumulated.

At the close of Pliocene time deposition ceased and a period of deformation began during which the Socorro and Los Pinos Mountains were upfaulted relative to the adjacent basins and the Santa Fe beds were considerably deformed.

In Quaternary time, erosion during several cycles has carved the several pediments and terraces; and, finally, the modern flood plains and arroyos have been formed.

ACKNOWLEDGMENTS.—The work was undertaken at the suggestion, and has been carried out under the guidance, of Dr. Kirk Bryan, of Harvard University, to whom the writer is greatly indebted for encouragement and criticism in the field and laboratory. Many of the ideas contained herein have been contributed by Dr. Bryan. Dr. M. P. Billings, of Harvard University, was kind enough to read and criticize part of the manuscript in its original form. Professor E. D. Elston, of Dartmouth College, has been kind enough to criticize the manuscript. During 1935 the writer was ably assisted in the field by A. H. Smith, R. S. Folsom, and D. Rose; in 1936 by R. S. Folsom and K. M. Clark, Jr.; and in 1937 by C. E. Stearns. The Middle Rio Grande Conservancy District and Mr. Stanley Phillipi furnished maps and loaned a tripod. It is a pleasure to acknowledge the hospitality and many courtesies extended by residents of the area, especially Messrs. F. G. Fisher, H. E. Byers, and G. A. Eckerson, of Belen, Mr. R. Lloyd, of Abeytas, and Mr. R. H. Perry, of Magdalena.

REVIEWS

A Source Book in Geology. By KIRTLEY F. MATHER and SHIRLEY L. MASON. New York: McGraw-Hill Book Co., 1939. Pp. 702. $5.00.

The purpose of this book, which is one of a series of source books in the history of the sciences under the editorship of Gregory D. Walcott, is to give a comprehensive view of the development of the geological sciences during the seventeenth, eighteenth, and nineteenth centuries. This has been accomplished by quoting directly some of the most significant passages from writings of the great contributors to the science in the past. The excerpts include small portions of the work of 130 geologists, each of whom was influential in molding the geological thought of his time. The original statements of many principles and theories are thus made available. Many of these are translated from Latin, French, German, or Italian, and some are taken from books not readily accessible to the student. For this reason it is a good, though inevitably limited, book of reference and supplementary reading.

Each contributor is treated separately and without comment from the authors other than a perhaps too brief biographical note. The thread of development of the science would have been easier to follow if the authors had accompanied the excerpts with a few comments of their own and had arranged them according to the dates of their appearance and influence rather than chronologically according to the birth dates of the contributors. The quotations begin with Leonardo da Vinci and end with Charles Richard Van Hise, including no publications later than 1900 and none from scientists now living.

A guide to the subject matter is also given, and in this way the contributors are divided into thirty-two groups, which give a representative section through the field of geology.

LOUISE BARTON FREEMAN

Moskenesøy: A Study in High Latitude Cirque Lakes. By KAARE MÜNSTER STRØM. ("Skrifter utgitt av Det Norske Videnskaps-Akademi," I, "Matematisk-Naturvidenskapelig Klasse," No. 1.) Oslo: i Kommisjon Hos Jacob Dybwald, 1938. Pp. 32; pls. 4; figs. 14.

The island of Moskenesøy, one of the Lofoten group off the coast of northern Norway, is composed of igneous rocks which have been highly

dissected by local glaciation. Cirques are very numerous, and nearly all of them contain lakes of unusual depths. These have been made the subject of a special study. Numerous charts and tables show in detail the data observed in respect to the bathygraphy, hydrology, electrolyte content, temperature, and bottom deposits of the several lakes which were studied. A submerged platform from 60 to 30 meters below the present sea-level is believed to represent the outer half of the island which was eroded away during an earlier stage of lowered sea-level.

RAYMOND E. JANSSEN

"The Eo-Cambrian Series of the Tana District, Northern Norway," by SVEN FØYN. (Reprinted from *Norsk Geologisk Tidsskrift*, Vol. XVII [1937], pp. 65–164.) Figs. 51; pls. 5; 1 map.

Tillites conformably underlying fossiliferous Cambrian strata occur at the head of Tanafjord east of North Cape on the northern coast of Norway and are a westward continuation of the tillites long known from the head of Varangerfjord.

The tillites, which are called Eo-Cambrian, occur as two extensive deposits separated by shales and sandstones. The lower tillite consists of a silt and clay matrix in which lie rock fragments ranging up to 2 meters in diameter. Most of these fragments are dolomite, with pre-Cambrian crystalline rocks second in abundance. Upon close examination the material is found to be somewhat assorted, although Caledonian folding has given the tillite a secondary schistosity which has partially effaced the traces of stratification. The boulders of the upper tillite are chiefly pre-Cambrian granites and gneisses, the dolomites here being of secondary importance. The sources of these materials lay toward the south. It is interesting to note that no amphibole has been observed among the minerals.

RAYMOND E. JANSSEN

Internal Constitution of the Earth. Edited by B. GUTENBERG. ("National Research Council, Physics of the Earth Series," Vol. VII.) New York: McGraw-Hill Book Co., 1939. Pp. x+413. $5.00.

Terrestrial Magnetism and Atmospheric Electricity. Edited by J. A. FLEMING. ("National Research Council, Physics of the Earth Series," Vol. VIII.) New York: McGraw-Hill Book Co., 1939. Pp. xii+794. $8.00.

The reviewer notes with regret that neither in the Foreword to Volume VII nor in that of Volume VIII is mention made of a volume treating

hydrology. The omission strikes him especially, since he was present at a meeting of the Hydrology section of the American Geophysical Union some years ago when a resolution urging such a volume was passed unanimously. Either his memory fails him, or he recalls a subsequent report that a subcommittee was at work upon such a project. It is to be regretted that no such volume is to be presented with the rest of the series, especially since the section particularly concerned is the largest and most active in the union.

In Volume VII, the present knowledge concerning the interior of the earth is reviewed. Perhaps the only adverse criticism that may be made is that it leans rather heavily toward a single version of earth genesis, the tidal hypothesis, and that the facts in support of a globe solid throughout growth are not brought out so clearly as might be.

The topics outlined are: "The Origin of the Solar System," by Harold Jeffreys; "Relevant Facts and Inferences from Field Geology," by R. A. Daly; "Elastic Properties of Materials of the Earth's Crust," by L. H. Adams; "The Crust of the Earth and Its Relation to the Interior," by H. W. Washington (revised by L. H. Adams); "Observed Temperatures in the Earth's Crust," by C. E. Van Orstrand; "The Cooling of the Earth and the Temperature in Its Interior," by B. Gutenberg; "Forces in the Earth's Crust," by B. Gutenberg; "Hypotheses on the Development of the Earth's Crust and Their Implications," by B. Gutenberg; "Evidence on the Interior of the Earth Derived from Seismic Sources," by James B. Macelwane; "Evidence from Deep-Focus Earthquakes," by B. Gutenberg and C. F. Richter; "Density, Gravity, Pressure and Ellipticity in the Interior of the Earth," by W. D. Lambert; "The Elastic Constants of the Interior of the Earth," by B. Gutenberg; and "Viscosity, Strength and Internal Friction in the Interior of the Earth," by B. Gutenberg.

Particular attention should be called to the chapter on "Evidences on the Interior of the Earth Derived from Seismic Sources," wherein James B. Macelwane has treated a highly technical subject in the simplest of language and without sacrifice of clarity.

The reviewer highly recommends the book to all structural geologists and others that are interested in the hypothetical concepts of megatectonic geology. It should be a source of indispensable information for one interested in mass movements within the earth, the ultimate causes of the major tectonic features, and the reasons for their spatial or temporal distribution. The contribution of field geology to the subject of the interior of the earth is clearly brought out by R. A. Daly in chapter iii

wherein he shows that much of the geological evidence is disappointingly negative.

Of the topics discussed in *Terrestrial Magnetism and Atmospheric Electricity*, only one is likely to be of deep interest to many readers of the *Journal of Geology*. The chapter entitled "Magnetic Prospecting," written by C. A. Heiland, is a complete and well-written summary of the present state of knowledge of that art. Other chapters deal with: "The Earth's Magnetism and Magnetic Surveys," by J. A. Fleming; "Magnetic Instruments," by H. F. Johnston, J. A. Fleming, and H. E. McComb; "Atmospheric Electricity," by O. H. Gish; "Instruments Used in Observations of Atmospheric Electricity," by O. W. Torreson; "Earth-Currents," by W. J. Rooney; "On Causes of the Earth's Magnetism and Its Changes," by A. G. McNish; "Some Problems of Terrestrial Magnetism and Electricity," by J. Bartels; "Radio Exploration of the Earth's Outer Atmosphere," by L. V. Berkner; "The Upper Atmosphere," by E. O. Hulburt; "The Aurora Polaris and the Upper Atmosphere," by L. Vegard; "Thunder-clouds, Shower-clouds, and Their Electrical Effects," by B. F. J. Schonland.

The volume is well written, contains a remarkably complete Bibliography (arranged by H. D. Harradon), and is bound in accord with the other volumes of the series. The authors, the editor, the National Research Council Committee, and the publishers are to be congratulated upon both Volume VII and Volume VIII of the "Physics of the Earth Series."

H. W. STRALEY, III

Studies on the Ice Age in India and Associated Human Cultures. By H. DE TERRA and T. T. PATERSON. Washington, D.C.: Carnegie Institution of Washington, 1939. Pp. 354; figs. 193; pls. 56.

This comprehensive report deals with the geologic and archeologic results of an expedition sponsored by the Carnegie Institution of Washington, Yale University, Cambridge University, and the American Philosophical Society and carried out in 1935 under the direction of Hellmut de Terra, in association with T. T. Paterson and P. Teilhard de Chardin. The purpose of the expedition was to study the Ice Age cycle in the Himalaya and to attempt to unravel the Pleistocene history of Stone Age man in other parts of India.

The report is divided into five parts covering different geographic areas. The first, "The Ice Age in Southwestern Kashmir," is the longest

and most complete, giving the geographic and geologic backgrounds to the more detailed work on the glaciation and prehistoric man. Included in this part also is a section on the petrology of the Karewa lake beds, their sedimentation and genetic significance, written by Paul D. Krynine. The other parts are titled as follows: "Pleistocene Geology and Stone Age Cultures in Northwest and Peninsular India," "The Pleistocene in the Narbada Valley of Central India," "Stratigraphic and Typologic Sequence of the Madras Paleolithic Industries," and "The Late Stone Age Sites at Sukkur and Rohri, on the Lower Indus in Upper Sind."

All sections are amply illustrated with geologic maps of small areas which have some particular importance, with geologic cross sections showing the relations of the various formations to the evidences of human cultures, and with very fine photographs which are grouped at the end of the volume.

LOUISE BARTON FREEMAN

"Ash Formations of the Island Hawaii," by CHESTER K. WENTWORTH. *Third Special Report of the Hawaiian Volcano Observatory.* Honolulu: Hawaiian Volcano Research Association, 1938. Pp. viii+183; pls. 10; figs. 16.

Geologically, Hawaii, the largest island of the Hawaiian group, is divided into five regions, corresponding in areal extent to the five principal volcanic domes. These are Mauna Loa and Mauna Kea, which make up the greater area of the island, and Kohala, Hualalai, and Kilauea, which are of lesser extent. On the basis of original volcanic forms, each of these has been further subdivided into geomorphic areas totaling thirty in number.

The publication discusses in detail the physiography of the island, the nature of the pyroclastic processes and products, the distribution and structure of the pyroclastic formations, the petrography of the volcanic rocks, and the eruptive history and origin of the respective formations.

Among the several problems arising from the study of the pyroclastic history of the island, the most important is the origin and source of the Pahala tuff and its relation to the Waiau tuff. Studies indicate, but do not prove, that the major parts of the Waiau and Pahala tuffs are a single formation. This is believed to have originated from the summit eruptions of the Mauna Kea cones and is thought to be of Pleistocene age. The history of the island extends back into the Tertiary.

RAYMOND E. JANSSEN

Leaves and Stems from Fossil Forests. By RAYMOND E. JANSSEN. ("Popular Science Series, Illinois State Museum.") Springfield, Ill., 1939. Pp. 190; figs. 165.

This volume is subtitled "A Handbook of the Paleobotanical Collections in the Illinois State Museum," and is the first of a series of guidebooks formulated by the Museum to fill the need of science teachers, students, and laymen interested in the fossil plants of the state. The author has been successful in presenting scientific information in simple, direct language suitable for the nonspecialist without losing scientific accuracy.

The first of the nine chapters gives a brief background for the more detailed descriptions to follow and covers methods of fossilization, the collection of fossils, and the classification of plants. The next six chapters are occupied with descriptions of the most common species found in the Illinois Pennsylvanian. These descriptions can be used for identification purposes, since they are clear, concise, and well illustrated with excellent photographs of specimens and in some cases diagrammatic drawings to emphasize differences in closely related species. The book ends with a bibliography and a good index, which is essential to a handbook of this type.

LOUISE BARTON FREEMAN

Contributions to the Paleobotany of Middle and South America. By EDWARD W. BERRY. ("Johns Hopkins University Studies in Geology," No. 13.) Baltimore: Johns Hopkins Press, 1939. Pp. 168; figs. 3; pls. 23. $2.00.

Six papers make up this volume, five having been written by Berry. The sixth is a short paper by Henry A. Pilsbry, entitled "Freshwater Mollusca and Crustacea from near El Molino, Bolivia," which accompanies the first and longest report of the book, "The Fossil Flora of Potosí, Bolivia." The fossil plants so described were collected from tilted lake beds of volcanic ashes on the western slopes of Cerro Rico de Potosí.

The titles of the other papers are: "The Fossil Plants from Huallanca, Peru"; "A Miocene Flora from the Gorge of the Yumuri River, Matanzas, Cuba"; "Fossil Plants from the State of Anzoategui, Venezuela"; and "Eocene Plants from a Well Core in Venezuela."

LOUISE BARTON FREEMAN